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Methods in Ecology and Evolution

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Article type : Research Article

Editor : Claudia Coleine

On the measurement of microclimate

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Running title: microclimate measurement

Abstract

1. Many organisms live in environments in which temperatures differ substantially from those measured by standard weather stations. The last decade has witnessed a paradigm shift in efforts to quantify these differences and to understand their ecological, functional and evolutionary implications. This renewed interest in microclimate ecology has been accompanied by the development of various compact temperature sensors and radiation shields. However, it is clear that there are many pitfalls when measuring temperature using these devices.
2. Here we address the problem of measuring temperatures in these microenvironments accurately. We first discuss the theory of measuring surface, ground and air temperatures with reference to energy fluxes and how these are modified by material, reflective properties, and size of the device. We highlight the particular difficulties associated with measuring air temperature. We then report on the results of a series of experiments in which air temperatures recorded by various commonly used microclimate temperature loggers are compared to those obtained using research-grade instruments and synoptic weather stations.
3. While accurate measurements of surface and ground temperatures and air temperatures at night and in shaded environments can be relatively easily obtained, we show substantial errors are to be expected when measuring air temperatures in environments exposed to sunlight. Most standard sensors yield large errors, which can reach 25°C due to radiative fluxes operating on the thermometer. This problem cannot be wholly overcome by shielding the thermometer from sunlight, as the shield itself will influence both the temperatures being measured and the accuracy of measurement.
4. We demonstrate that reasonably accurate estimates of air temperature can be obtained with low-cost and unshielded ultrafine-wire thermocouples that possess low thermal emissivity and a highly reflective surface. As the processes that create microclimatic temperature variation are the same as those that cause errors, other logger types should be used with care, and generally avoided in environments exposed to sunlight and close to the ground where wind speeds are lower. We urge researchers interested in microclimates and their effects to pay greater heed to the physics of heat exchange when attempting to measure microclimate temperatures and to understand the trade-offs that exist in so doing.

Key words: air temperature, climate change, ecology, ground surface temperature, microhabitat, microrefugia, soil temperature, thermocouple

Introduction

Temperature influences every aspect of the physical environment within which terrestrial, freshwater and marine organisms reside. It sets limits on the survival, reproduction and behaviour of organisms and governs the rates of biological processes within these limits (Clarke, 2017). The increasing availability of global gridded climate data ─ e.g. ERA5 (Copernicus Climate Change Service, 2020), WorldClim (Fick & Hijmans, 2017), CHELSA (Karger et al., 2017) and Terraclimate (Abatzoglou et al., 2018) ─ interpolated from weather stations, has greatly facilitated macroecological research on links between organisms and climate. However, many organisms live in environments with temperatures that differ substantially from those of weather stations (Suggitt et al., 2011), as close to the ground or the surface of vegetation, temperatures are influenced strongly by radiative fluxes. Similarly, temperatures in open environments can differ substantially from those measured in the shade below vegetation, where understory plants and animals are often buffered from the extreme temperatures experienced in open areas (De Frenne et al., 2019). Reliable estimation of microclimatic conditions is thus key to understanding how organisms interact with their environment, and is increasingly recognised as necessary for addressing applied challenges such as predicting the ecological consequences of climate change (Potter et al., 2013; Zellweger et al., 2020). Growing recognition of the importance of this discrepancy has led to a paradigm shift towards microclimate ecology and biogeography (Lembrechts & Lenoir, 2020). Yet, many ecologists do not seem fully aware of the pitfalls associated with measuring microclimate.

Let us first consider the measurement of air temperature by a weather station. In 1954, the World Meteorological Organisation published the first edition of the 'Guide to Meteorological Instruments and Methods of Observation', which sets out standardized procedures for measuring air temperatures (WMO, 1954). Since radiation from the sun, clouds, the ground and other surrounding objects passes through air without appreciably changing its temperature, but a thermometer exposed freely in the open can absorb considerable radiation, it is thus deemed necessary to protect the thermometer from radiation by a screen or shield. Without doing so, temperature differences between the air and a thermometer may reach 25°C (WMO, 1954). It is recommended that the size and construction of the screen is such that it allows ample space between the thermometer and the walls of the screen and that direct contact between the sensing elements and thermometer mounting is avoided to prevent conductive heat transfer. The screen itself is painted white or made of reflective material, and artificially ventilated and/or, more commonly, louvred to permit natural ventilation, thereby ensuring that convective heat exchange between the thermometer and the air inside the screen, and between the air inside the screen and that outside it, is maximised. It is also recommended that air temperature should be representative of the free air conditions surrounding the station over as large an area as possible. As such, temperatures are recorded at a height of between 1.2 and 2.0 m above ground level in locations that are freely exposed to wind and unobstructed by nearby vertical objects in the landscape such as trees, buildings and surrounding terrain. In other words, microclimatic “noise” is deliberately minimised. Yet, what is considered “noise” by climatologists matters for biologists interested in biotic responses to climate.

Let us now consider air temperature close to the ground or vegetation. Just above the ground close to other opaque surfaces such as rocks, soil and leaves, conductive and convective heat transfer leads to significant fine-scale variation in air temperature, because reduced airflow maintains strong vertical and horizontal gradients in temperature (Richardson 1922; Geiger, 1927; Monin & Obukhov, 1954). If the intention is to measure temperature in environments exposed to radiation, then the issue of radiation absorption arises: when exposed to solar radiation, the temperature of an unshielded thermometer will be influenced by these radiative fluxes.

The issue of radiation fluxes operating on temperature loggers has prompted many ecologists to deploy radiation shields (Table 1). However, this can be problematic for two reasons. Firstly, whereas at the height of a standard weather station, airflow generally ensures that the temperatures underneath a shield are similar to those of its surroundings, this is not the case when microclimatic variation exists. Here, the temperature variation owes its existence to low wind speed (Geiger, 1927; Prandtl, 1953) and a shield will alter the temperature through shading and reduced wind speed. Consequently, the temperature being measured ceases to be representative of that in the absence of a shield. Mechanical ventilation through the use of an aspirator is also not a solution. Artificially increasing the airflow alters the convective heat exchange processes that are ultimately responsible for microclimatic variation (Prandtl, 1953), and thus alters the temperature of the air itself. Secondly, whereas a standard weather station is large enough to ensure that convective heat transfer between the shield and thermometer is negligible, the measurement of microclimate temperatures has often involved the deployment of miniaturised shields (Table 1). Here, the thermometer and shield are either separated by a small distance or in direct physical contact with one another. Temperature measurements are thus influenced by the temperature of the shield, which itself absorbs radiation.

Faced with these challenges, biologists have used a variety of approaches (Table 1). It is clear that there is often a degree of misunderstanding of the issues affecting microclimate temperature measurements and that little guidance on best practices exists. The aim of this paper is to offer this guidance. We first provide a theoretical overview of the factors that affect the temperature of a thermometer, and show how these can be calculated. We then report on the results of three independent experiments in which air temperatures recorded by various commonly used microclimate temperature loggers (here defined as the data logger or storage unit, together with the sensor) are compared to those obtained using research-grade instrumentation. Whereas measuring below ground temperatures or the surface temperature an object in direct physical contact with thermometer is relatively unproblematic, we demonstrate that the majority of the current approaches used to measure air temperatures in microclimate studies potentially yield erroneous measurements, particularly in circumstances where microclimate air temperatures differ most from those that would be measured by standard weather stations in the same environment, such as close to the ground in open habitats. Better methods do, however, exist. We thus conclude by offering guidance on how microclimate air temperatures can be easily and fairly accurately measured using consumer-grade devices.

The physics of thermometer heat exchange

Thermometer temperature

An equation that describes the error in temperature measurement of a thermometer (ΔT) can be derived from Fourier's Law of heat transport (Campbell & Norman, 2012; Monteith & Unsworth, 2013; Appendix1 in Supporting Information):

$$\Delta T + \frac{R_{abs} - R_{em}}{k_{\Delta z}} \qquad (1)$$

where R_{abs} and R_{em} are absorbed and emitted radiation ($W \cdot m^{-2}$), respectively and $k_{\Delta z}$ is the conductivity ($W \cdot m^{-1} \cdot °C^{-1}$) over distance (m). Assuming our purpose is to measure temperature as closely as possible, an accurate device will thus have high thermal conductivity and minimise the effects of the absorbed and emitted radiation. Let us now consider each of these terms in detail.

Thermal conductance

Heat transfer is usually measured in units of $W \cdot m^{-2}$. When two objects are in direct contact, heat is transferred by conduction ─ a process in which thermal energy is transferred by the collisions of molecules to propagate energy from hot to cooler mediums ─ just like when walking bare foot on a hot sandy beach. This form if heat transfer is relevant to consider when determining, for example, the exchange of heat between a thermometer and a leaf or rock in direct physical contact with the thermometer or when considering how a thermometer might be influenced when physically in contact with a radiation shield. Here the heat transfer ($W \cdot m^{-2}$) is the product of the conductivity (k, in $W \cdot m^{-1} \cdot °C^{-1}$) between the surface and heat sensing element of a thermometer and the temperature gradient ($°C \cdot m^{-1}$). It is thus influenced by both the distance over which heat must travel and the thermal conductivity of the substance through which the heat travels. Copper, for example, has a higher conductivity than plastic. Conversely, it can be seen that the error in measurement (the difference between the temperature of the surface and that of the thermometer) is thus the heat transfer to the thermometer in form of radiation divided by the product of the conductivity and the distance through which heat must travel. Strictly speaking it is also necessary to consider the surface area in contact, as this scales the rate of heat transfer per unit area to the overall rate of heat transfer. In practical terms, however, any gains from using a larger thermometer in terms of increased heat exchange between the thermometer and the surface, are counteracted by the increases in radiative energy received. Irrespective of the surface area of the thermometer, since it is usually possible to maintain a very small distance between the heat sensing element of the thermometer and the surface being measured, the overall conductivity per unit distance is very high and the errors caused by radiative fluxes are minimal.

When measuring the temperature of soil below the surface, no radiative heat is supplied to a thermometer and the errors in measurement are likely to be negligible. Her the primary consideration is the any water-proof casing surrounding the thermometer, which may impede the conductance of heat and thus decrease the rate at which a thermometer's temperature attains equilibrium with that of the soil. Nevertheless, except near the soil surface, rates of change in temperature are relatively slow (Campbell, 1985). In consequence, even when housed in relatively solid casing made of a material with low conductivity, the temperature of a thermometer will generally attain equilibrium with that of the soil. However, weather proof casing surrounding a thermometer will affect its ability to accurately determine surface temperatures above ground. Here, conductance between the surface and thermometer is imbedded, but the casing still receives radiative heat and transfers this heat to the thermometer itself.

For a thermometer suspended in a fluid such as air, however, the predominant heat transfer mechanism is by convection. This involves conduction between a substance and the fluid, simultaneously accompanied by transport of heat to or from the fluid. Equation (1) can still be applied, but since the temperature gradient at the surface is maintained by the velocity of the fluid, conductivity must be appropriately defined. Here, the overall rate of heat transfer is the defined by Fick's Law and is the product of the volumetric specific heat of the fluid ($J \cdot m^{-3} \cdot °C^{-1}$), its conductance (*K* expressed in $m \cdot s^{-1}$ ─ see Appendix 1 in supporting information for an explanation of the different units of measurement used) and the temperature difference between the fluid and the thermometer. Conversely, therefore, the error in measurement is thus the net radiative heat transfer to the thermometer divided by the product of the conductance and its volumetric specific heat. In contrast to the situation in which a thermometer is in direct surface contact with the substance, the conductance is not so high, and the radiative fluxes become important (Campbell & Norman, 2012). This is true in both air and water. Though in water, a significant portion of the radiation is attenuated, and the volumetric specific heat of the fluid is higher, overall conductive heat transfer is only c. 20% as efficient in water as in air owing to the much lower thermal diffusivity and kinematic viscosity of water (Appendix 2).

The conductance of fluids depends on the nature of the convective currents. Convective currents are categorised as either laminar or turbulent depending on the pattern of movement of fluid particles. Laminar flow is most relevant to consider in the example of a thermometer suspended in a fluid, and is characterised by the layered movement of fluid particles. Each layer moves smoothly past the adjacent layers and heat is transferred across streamlines only by molecular diffusion. Laminar flow is either free or forced depending on how the fluid motion is initiated (Von Karman, 1946). In forced convection, the fluid is forced to flow over a surface, which in the terrestrial environments is caused by wind or in aquatic environments by gravity and river flow. In free convection, any fluid motion is caused by natural means via buoyancy, i.e. the rise of warmer fluid and fall of cooler fluid generating a circular movement. A typical example of such circular movements is water in a heated saucepan. Conduction under forced convection is generally greater than under free convection, and also increases with the strength of the wind (Appendix 2 in Supporting Information). Thus, close to the ground, where wind flow tends to be much lower, the influence of absorbed and emitted radiation on the temperature of a thermometer will be greater as the thermometer is less able to exchange heat with the air. Conductance also decreases as the size of the thermometer increases (Appendix 2 in Supporting Information), as there is more potential for airflow along the object to develop into orderly laminar layers. Thus, size matters and only very small thermometers would be expected to provide accurate temperature measurements in areas with low wind speed (Fig. S1a).

In turbulent flow, rapidly fluctuating eddies (i.e., small whirlpools or vortices) transport heat, as occurs where the layered movement of fluid particles breaks down. This is relevant when considering heat transported through louvered radiation shields in open areas, for example, where the air is naturally turbulent. It thus dictates the extent to which the temperature of the air underneath the shield is similar to that away from the shield and, as with laminar flow, increases with wind speed. The equations that govern turbulent flow also determine the wind profile above ground, which typically increases logarithmically with height. Since turbulent conductance also increases with wind speed, close to the ground a thermometer will be influenced more strongly by radiation emitted by the shield (Fig. S1b).

Radiation

Radiation is generated by the thermal motion of particles in matter and no intervening medium is required for heat transfer. It is the underlying reason that one feels warmer in sunshine – here one's body is absorbing solar radiation. Any radiation received by an opaque object is then either absorbed or reflected, the latter depending on the wavelength-specific reflectance of the surface. Materials such as white plastic, polished steel or aluminium typically have a shortwave reflectivity of 75-90%, whereas darker surfaces on average absorb more than 90% of shortwave radiation (Tarara, 2000), and hence reflect only 10%. All objects also emit radiation as a function of their absolute temperature to the power of four. Absorption of radiation causes an object to heat up, and thus emit more radiation.

The radiation received by a thermometer has three sources. The first is radiation from the sun, which can reach the surface of a thermometer either directly, or in the form of diffuse radiation, which is scattered by particles and clouds in the atmosphere. Direct radiation received by a thermometer depends on the angle of the surface relative to perpendicular. Thus, close to solar noon, the radiation absorbed by a horizontal thermometer will be greater. Diffuse radiation depends instead on the fraction of the hemisphere in view (Campbell & Norman, 2012). Thus, even on a cloudy day, the radiation absorbed by the thermometer will be greater in unshaded environments. The second source is solar radiation reflected from surrounding surfaces, which in turn depends on the reflectance or albedo of those surfaces (the reflectance of objects is wavelength specific, and albedo is the average reflectance of radiation in the shortwave spectrum). For example, ice and snow have a high albedo and reflect far more radiation than rock, bare soil and asphalt (Hay, 1993). The final source is longwave radiation emitted from surrounding surfaces such as vegetation, soil and the sky. This in turn depends on the temperatures of those surfaces, the proportion of each surface in view. A radiation shield will also emit longwave radiation, some of which is received by the thermometer even when sufficient distance is maintained so as to limit convective heat transfer.

Emitted radiation, in addition to temperature, depends on the emissivity of the object. Emissivity is one minus its reflectivity, so surfaces with low emissivity at a given wavelength have high reflectivity at that wavelength and vice versa and since emitted radiation by passively heated objects is in the longwave spectrum, it is reflectivity and emissivity in the longwave spectrum that this relevant. Whereas metals also have relatively low emissivity (and high reflectivity) of longwave radiation, the converse is true of plastics (Tarara, 2000). An ideal temperature sensor should therefore have a surface coating of polished metal.

Materials and methods

Overview of experiments

Since the measurement of air temperature is most problematic, three sets of experiments were conducted to determine the accuracy of so doing. Our intention was to test a range of different types of temperature loggers and shields used commonly in ecological research (Table 1, Figs. S2-4). The experiments were designed to complement one another, each testing different facets of microclimate air temperature measurement. Experiment 1, conducted between 7th April and 10th July 2020 over several short intervals (Table S1) in Cornwall, UK (50.1739°N, 5.1042°W), was intended to quantify errors yielded by different logger types close to the ground in an open grassland. This is an environment where errors would be expected to be high owing to low wind speeds and high radiative fluxes operating on the temperature sensing elements of the logger. Results were compared with those from an ultrafine-wire thermocouple designed for obtaining atmospheric temperature fluctuations with research-grade accuracy. Having established the accuracy of consumer-grade ultrafine-wire thermocouples, in the second experiment, conducted between 1st May and 10th July 2020 in Leuven, Belgium (50.8217°N, 4.7336°E), we quantified errors yielded by other logger and shield types over several months, in both open grassland and closed-canopy mixed forest and at different heights above ground. Here our intention was to explore in greater depth the extent to which errors yielded by different sensor types vary in different environments. In the third experiment, conducted between 22nd December 2017 and 2nd August 2020 in Gontrode, Belgium (50.9803°N, 3.8160°E) our intention was to determine whether consumer-grade sensors and radiation shields can be used in place of a weather station. Here long-term temperatures obtained using loggers with two types of commonly-used consumer-grade radiation shields were compared to measurements obtained by an official synoptic weather station. Measurements were obtained at the same height above ground as the weather station as the intention was to investigate whether consumer-grade devices can be used in place of weather stations to accurately distinguish between air temperatures in open areas and those in those in forested environments.

Temperature loggers and shields tested

In Experiment 1, measurements obtained using a research-grade ultrafine-wire thermocouple were compared with those obtained using consumer-grade ultrafine-wire thermocouples, standard unshielded Lascar thermocouples and iButton thermochrons. We deployed unshielded iButtons, and iButtons shielded with (i) aluminium foil, (ii) 25.1 mm diameter PVC tubing and (iii) translucent open-ended film canisters. Both unshielded and shielded (using the shield provided by the manufacturer) TMS4 dataloggers were also compared. In Experiment 2, we assumed, based on the results from Experiment 1, that the consumer-grade thermocouples are sufficiently close to the real temperature to use them as a reliable reference. We thus compared measurements obtained using consumer-grade ultrafine-wire thermocouples with those obtained using TMS4 dataloggers (with and without shields) and iButton thermochrons: (i) no treatment, (ii) shielded with 10 cm diameter x 15 cm long horizontal white PVC tube following the design of Zellweger et al., 2019 and (iii) coated in transparent liquid rubber). In Experiment 3, we compared measurements obtained using Lascar loggers with internal thermometers with two types of shield. Since the thermometers were shielded and at reference height, the nature of the thermometer is of less importance, and it is the shield type that becomes relevant. The first shield type was the same as that used in Experiment 2. The second, a cone-like, home-made shield consisting of two white funnels on top of each other. The bottom funnel had holes to stimulate passive air displacement (following the design of Hubbart, 2011). Full details of the loggers used in each experiment are provided in Table 2.

Experimental set-up

In Experiment 1, air temperatures were measured 10 cm above a short grass lawn. Apart from the TMS4 loggers, each sensor was attached to a thin garden stake, and suspended c. 10 cm above the grass. This was achieved by counterweighting the stake on the surface of a concrete block located c. 10 cm away from the measurement area. TMS4 loggers were positioned in the ground c. 1 m away from other loggers, and inserted into the ground partially so that the above ground sensor, used in this experiment, was also 10 cm above ground. Research-grade equipment was programmed to obtain 20 temperature readings per second for 30 seconds at 10-minute intervals. Consumer-grade thermocouples were programmed to record temperatures at five second intervals and the iButton thermochrons and TMS4 dataloggers to record temperatures at one-minute intervals. The number of devices of each type deployed on each occasion is shown in Table S1. To provide a proxy estimate of the effect size being measured, namely differences from macroclimate, we sourced 25 km grid resolution hourly ambient air temperature data for the same location and time-periods from ERA5 (Copernicus Climate Change Service, 2020) and compared these temperatures to those obtained using the research-grade ultrafine-wire thermocouple.

In Experiment 2, the set-up was duplicated in two vegetation types (175 m apart): an open grassland and a mixed forest dominated by *Fagus sylvatica*, *Pinus sylvestris* and *Betula pendula* (canopy cover ~70%). In the grassland, grass was held short by clipping it weekly. Air temperatures were measured at hourly intervals at 2, 15 and 150 cm above ground surface, with each height treatment replicated six times. For measurements at 150 cm, dataloggers were installed on a wooden pole. To provide a proxy estimate of the difference between microclimate and macroclimate temperature, we calculated the offset between the measurements of the treatments at every height and the measurements made using the consumer-grade thermocouple at 150 cm in the grassland.

In Experiment 3, air temperatures were measured using Lascar loggers with internal thermometers at hourly intervals at 2 m height in an open field next to an official synoptic weather station. Measurements using each shield type were replicated three times. Part of the purpose of the experiment was to compare between open habitats and nearby forest. The set-up was thus duplicated in a deciduous forest less than 1 km away from the open site (50.9750°N, 3.8043°E). The forest site was dominated by *Quercus robur* and *Fagus sylvatica* with minor canopy cover contributions by *Acer pseudoplatanus*, *Fraxinus excelsior* and *Larix decidua*. We compared the errors in measurement to the differences between the forest and open site.

Results

Experiment 1

During periods of bright sunshine, both research- and consumer-grade ultrafine-wire thermocouples detected large fluctuations in temperature caused by eddy turbulence (Fig. S5). When averaged over hourly periods, however, only the consumer-grade ultrafine wire thermocouple gave estimates of hourly temperatures comparable to the research-grade thermocouple, with a root-mean-square (RMS) error of 0.93°C. All other devices, irrespective of them being shielded or not, resulted in measurements that in general differed from those obtained using the research-grade thermocouple by an amount that exceeded our proxy of the effect size being measured (Table 3; Fig. S6). Both shielded and unshielded iButton thermochrons yielded substantial differences from the research-grade thermocouple, with the difference of unshielded iButtons on occasion exceeding 15°C. More accurate readings were obtained by shielding iButtons, but even when shielded, the RMS error was never lower than 3.16°C. Shielding had little effect on the accuracy of the TMS4 dataloggers, which in both cases gave measurements closer to those obtained by the research grade thermocouple than iButton thermochrons. Nevertheless, overestimation of temperatures of ~9°C were recorded by both shielded and unshielded loggers, though the RMS error both when shielded and unshielded was lower: 2.7°C. Variation in temperatures measured by each device over a typical 24-hour period (12^{th} July 2020 GMT) is shown in Fig. 1. Full results are shown in Table 3. Errors were generally larger during the day than at night, with RMS errors of the latter for all logger types, around or below 1.5°C.

Experiment 2

At the grassland site, the accuracy of hourly temperature measurements obtained using the TMS data loggers (relative to measurements obtained using consumer-grade ultrafine wire thermocouples) was considerably greater than that of iButton thermochrons at all heights, with the greatest accuracy achieved by the shielded TMS4 data logger (Fig. 2, Table 4). The iButton thermochrons consistently over-estimated temperatures during the day, particularly when unshielded and coated, with errors reaching 25.96°C (unshielded) and 18.50°C (coated). The iButtons housed in PVC tubes generally performed better than unshielded iButtons, though temperatures were consistently over-estimated both during the day and at night. Both shielded TMS4 dataloggers systematically over-estimated temperatures in sunny conditions, though errors were larger for unshielded dataloggers (Fig. 2).

At the forest site, overall accuracy was higher, but the accuracy of hourly temperature measurements obtained using the TMS4 data loggers was again consistently greater than that of iButton thermochrons at all heights, with greatest accuracy achieved by the shielded TMS4 data logger, which gave reasonably accurate estimates. The iButton thermochrons again over-estimated temperatures during the daytime. Though temperatures were more accurately estimated in the forest environment, the difference between near-ground microclimate temperature and those at reference height as measured by weather stations in open areas are also lower in forest environments. Only the shielded TMS4 datalogger yielded errors that were consistently smaller than this difference (Figs. 3 and S6). Full results for both habitat types, each height and each logger and shield combination are shown in Table 4. Temperature comparisons during representative sunny and cloudy periods are shown in Fig. 2 and over the duration of the study in Fig. S5. Errors computed for daily maxima and minima and during selected cloudy and sunny periods are shown in Tables S2-5.

Experiment 3

Maximum daily temperatures recorded in the open area using the Lascar loggers with internal thermometers shielded by home-made shields were frequently over-estimated by several degrees in comparison to temperatures obtained by the synoptic weather station, particularly when the funnel shield was used (Fig. 4; Table 5). Mean daily temperatures were also over-estimated, though by approximately half the amount, and again temperatures were over-estimated more when the funnel shield was used. Minimum temperatures were relatively accurately estimated irrespective of which shield was used. Daily and monthly RMS and maximum errors for both shield types are shown in Table 5. In general, the temperatures measured using consumer-grade devices in the forest environment were much closer to those measured using the synoptic weather station in the open environment, despite the expectation that significant habitat effects would be evident (Fig. 4).

Concluding discussion and guidance

The physics of thermometer heat exchange demonstrate that it is the measurement of microclimate air temperatures that is most problematic. Below the surface of the soil, radiative fluxes do not affect the temperature of a thermometer and when a thermometer can be placed in direct physical contact with a surface, conductance is high, and the radiative fluxes become less important. But how should one measure microclimate air temperatures, and how much error can one expect in so doing? From a theoretical perspective, three properties of a thermometer influence its accuracy. Firstly, as conductance is inversely related to the size of the device, a very small thermometer will obtain more accurate readings. Since wind speeds close to the ground are generally low (Campbell & Norman, 2012; Geiger, 1927; Monin & Obukhof, 1954), only the very smallest of devices, e.g. thermocouples of less than 0.1 mm thickness, will be able to obtain accurate measurements in sunlight. A second factor of importance is the thermometer's solar reflectivity. Surfaces with a high reflectivity, such as polished steel, aluminium or white plastic, absorb relatively little solar irradiance. Thermometers or temperature probes made of highly reflective surfaces are thus likely to perform better than those with darker surfaces. Finally, thermal emissivity affects the extent to which the thermometer will underestimate air temperatures in the absence of solar radiation, but will determine the absorption of longwave radiation from surrounding surfaces since emissivity and absorptivity are equivalent. While metals have relatively low thermal emissivity, plastics have high thermal emissivity (Tarara, 2000) and thus weather-proofing a thermometer using plastic casing is potentially problematic. In terms of reflective properties and size, both the device measuring temperature and the logger itself are important, with the relative importance of each depending on the extent to which they are thermally isolated from one another. An ideal thermometer should thus be as small as possible, have a surface coating of polished metal and should be thermally isolated from the data storage unit and housing. Empirically, however, we show that iButtons are likely to yield measurements that differ substantially from those obtained using research-grade equipment. This is likely due to a high proportion of the thermal heat emitted by the temperature sensor element of the iButton being absorbed and remitted by the black plastic casing on the interior surface of the logger.

If estimates of air temperature in sunny and low-wind environments are required, our results demonstrate that standard non fine-wire devices often used in ecological research are not well-suited to this purpose. Notwithstanding that our experiments were conducted in environments where radiative fluxes are not at their most extreme, for the most part, errors are so large that they exceed the differences between ambient air temperature and microclimate temperature. Even in partially sunny conditions, errors of several degrees can be expected. Shielding the device from radiation offers only a partial and unsatisfactory solution. The radiation shield itself absorbs radiation and is rarely sufficiently thermally isolated from the thermometer to prevent interference. The shield will also influence the very microclimatic conditions being measured. Shields are thus most appropriate to use where localised temperature differences from the surrounding air are of less concern, and where wind speeds are sufficiently high to ensure thermal mixing. To limit heat exchange between the sensor and the shield, a sufficient distance between the shield and the sensor must be maintained, particularly in low-wind environments.

Overall, we recommend that in sunny environments an ultra-fine wire thermocouple is used. The consumer-grade ultrafine-wire thermocouple tested in this study provides estimates of temperature with adequate accuracy for most purposes, and substantially greater accuracy than the majority of devices used more commonly. We show, however, that miniaturised thermocouples will be prone to measuring rapid, random fluctuations in air temperature, which can be significant above heated ground owing to the turbulent nature of heat transfer (Campbell, 1969). Since ultra-fine wire thermocouples are likely to be responsive to these temperature fluctuations, it is necessary to set a frequent recording interval, such that 30 measurements or more are obtained for each period for which average temperature is required. At night or in shaded environments the problem of radiation absorption is less severe, and the TMS4 dataloggers provided reasonably accurate estimates of temperature. There is little to differentiate between whether the devices should be deployed with shields or not. In the first experiment, greater accuracy was achieved when the TMS4 loggers were unshielded, though in the second experiment greater accuracy was achieved when shielded.

Nevertheless, in many circumstances the purpose of collecting microclimate air temperatures is to quantify the difference from those that would be recorded by a standard weather station, for example by endeavouring to estimates near the ground surface. It is generally the case that the factors contributing to this difference are also those that result in errors of temperature measurement. Consequently, the effect size being measured and the degree of error are often correlated, and, with the exception of the fine-wire thermocouples, errors in measurements obtained by the loggers tested in this study approach, or even exceed, the effect size being measured. Likewise, if comparisons between habitats with different degrees of shading are being made, the measured difference is likely to comprise both real differences and apparent differences caused by differential sensor errors. If high accuracy is of most concern, again an ultrafine-wire thermocouple should be used, though in circumstances where this is unpractical, the TMS4 loggers are the most accurate alternative.

In summary, there is no perfect way to measure air temperatures in environments where thermometers are subject to radiative fluxes and wind speeds are low enough to limit conductance. In most ecological settings where spatial replication is needed, endeavours to measure temperature will inevitably have to make a trade-off between cost, ease of deployment and data retrieval and the desired accuracy of measurements. Consumer-grade ultrafine wire thermocouples will offer an affordable solution for most purposes. Nevertheless, in closed canopy environments the options available are wider, and in some circumstances the use of other logger types, particularly TMS4 dataloggers, is appropriate. Such circumstances are likely to arise when the measured effect sizes are large compared to the expected errors, such as may occur when regional or altitudinal variation in temperature is of primary concern. Overall, we urge ecologists to pay greater heed to the physics of heat transfer when attempting to measure air temperatures and to understand the trade-offs that exist in so doing. An improved understanding of these principles will reduce the risk that highly inaccurate measurements are taken.

Acknowledgments

This work was supported by the Met Office Hadley Centre Climate Programme (HCCP) funded by BEIS and Defra. SH is funded by a FLOF fellowship of the KU Leuven. SG was funded by the Research Foundation Flanders (FWO) (project G0H1517N). PDF received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (ERC Starting Grant FORMICA 757833). TV was funded by the Special Research Fund (BOF) from Ghent University (grant number 01N02817). JL received funding from the Agence Nationale de la Recherche (ANR) under the framework of the young investigators (JCJC) funding instrument (ANR JCJC Grant project N°ANR-19-CE32-0005-01: IMPRINT). JJL is funded by the Research Foundation Flanders (projects OZ7828 and OZ8323). We thank Katie Thurston for proof-reading the manuscript, Nicole Parr for help with setting up the UK experiment and anonymous referees for helpful comments.

Author contributions

IMDM conceived the ideas presented, performed analyses and wrote the paper. JD, SH, SG, PDF, TV and KVM designed and conducted the experiments and compiled experimental data. SH, SG and MWR compiled data for tables 1 and 2. JD prepared figures and contributed to analysis. JL and JJL contributed to developing the ideas. All authors helped refine ideas and contributed to writing.

Data availability

Microclimate sensor data used in three experiments. DRYAD entry https://doi.org/10.5061/dryad.h9w0vt4hk

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Table 1. Examples of the variety of devices and shielding methods used to measure microclimate temperatures (* = not specified). The full reference for in-table citations is included in supporting information.

Device	Model	Shielding	Variable	Study
HOBO H8 Pro	*	plastic cylinder & mesh	air temperature	(Tracol, Gutiérrez, & Squeo, 2011; Vanesste et al., 2011)
HOBO Pendant	UA-002-08	naturally shielded by tree	air temperature	(Latimer & Zuckerberg, 2017)
iButton	Hygrochron*	polystyrene lid with topside covered by aluminium foil	air temperature	(Hardwick et al., 2015)
iButton	Thermochron*	parafilm & white duct tape	air temperature	(Stark et al., 2017)
iButton	*	wrapped in foil	air temperature	(Suggitt et al., 2011)
iButton	DS1921G	PVC capsule with drilled hole & shaded under aluminium roof	air temperature	(Bradley-Cook & Virginia, 2018)
iButton	DS1921G	transparent plastic tool dip	air temperature	(Roznik & Alford, 2012)
iButton	DS1921G-F5	no shielding	air temperature	(Bladon et al., 2019)
iButton	DS1921G-F5 DS1923	white plastic pipe/white plastic cup	air temperature	(Greiser et al., 2020)
iButton	DS1923	inverted PVC jar with side holes	air temperature	(Ashcroft et al., 2012)
Kestrel	3000	no shielding	air temperature	(Joseph et al., 2016)
Lascar	EL-USB-1	white plastic pipe	air temperature	(Zellweger et al., 2019)
Lascar	EL-USB-1	funnel (as in Experiment 3)	air temperatue soil temperature	(Sanczuk et al., 2020)
Thermocouple	Type T	white reflective tape	air temperature	(Amat & Masero, 2004)
TidbiT	*	aluminium screen	air temperature	(Monteiro et al., 2011)
TinyTag Plus 2	*	no shielding	air temperature	(Kraus et al., 2018)
TOMST	TMS3	white plastic conical shield	air temperature	(Wild et al., 2019)
TOMST	TMS4	white plastic conical shield	air temperature soil temperature	(Vandvik et al., 2020)
iButton	DS1921G DS1923	plastic funnel (exposed dataloggers only)	air temperature soil temperature	(Scheffers et al., 2014)
TidbiT	*	no shielding	air temperature soil temperature	(Fekete et al., 2016)
HOBO XT	*	no shielding	soil temperature	(Morjan, 2003)
iButton	DS1921G	wrapped in parafilm	soil temperature	(te Beest et al., 2016)
TinyTalk	*	no shielding	soil temperature	(Ruckli et al., 2013)
TidbiT	*	no shielding	soil temperature & internal grass tussock temperature	(Monteiro et al., 2011)
HOBO Pendant	UA-002-64	no shielding	internal moss hummock temperature	(Turlure et al., 2009)
Apogee infrared radiometer	SI-111	no shielding	soil surface temperature	(Fung & Jim, 2019)

Thermocouple	Type J	no shielding	soil surface temperature	(Bestelmeyer, 2000)
HOBO Pendant	*	no shielding	bark surface temperature	(Coyle, 2017)
Thermocouple	Type T	no shielding	leaf surface temperature & internal leaf mine temperature	(Pincebourde et al., 2007)
TinyTag Plus	TGP-4500	no shielding	wall surface temperature	(Sternberg et al., 2011)

Table 2. Summary of devices used in the three experiments.

Thermocouple type	Experiment used	Make and model	Operating range (ºC)	Temperature resolution (ºC)	Max. sampling rate (seconds)	Power source	Data storage (no. readings)	Cost (€)	Pros and cons
Research-grade ultrafine-wire thermocouple	1	0.0127 mm Type E (chromal-constantan) and CR1000X logger. Campbell Scientific, Logan, UT, USA	-40 to +70	0.01	0.003	10 W solar panel	2^{36}	4,847	Very high accuracy. Very expensive.
Consumer-grade ultrafine-wire thermocouple	1,2	0.08 mm Type K (chromel-alumel) thermocouple attached to a Lascar USB data logger (EL-USB-TC, Lascar Electronics, Wiltshire, UK).	-75 to +250	0.5	1	Replaceable ½ AA battery	2^{15}	77	High accuracy, moderately inexpensive. Difficult to check if battery flat
Standard Lascar thermocouple	1	Type K housed in 1.5 mm x 100 mm stainless steel sheath attached to a Lascar EL-USB-TC data logger (Lascar Electronics, Wiltshire, UK).	~~-75 to +250~~ 0 to +200	0.5	5 1	Replaceable ½ AA battery	2^{15}	58	Low accuracy. Moderately Inexpensive. Difficult to check if battery flat
Internal Lascar thermometer	3	EL-USB-1, Lascar Electronics, Wiltshire, UK)	-35 to +80	0.5	10	Replaceable ½ AA battery	2^{14}	43	Low accuracy. Inexpensive. Difficult to check if battery flat
iButton thermochron	1,2	DS1921G, Maxim Integrated Products, Sunnyvale, CA, USA.	-40 to +85	0.5	60	Internal, long-life non-replaceable battery	2^{11}	26	Inexpensive, small. Very low accuracy. Data lost when battery flat
TMS4	1,2	TOMST, Prague, Czech Republic			60	Internal, long-	2^{19}	80	Fairly high accuracy,

			-40 to +60	0.0625		life non-replaceable battery			moderately inexpensive,

Table 3. Experiment 1. Root mean square (RMS) and maximum error of aggregated hourly temperature measurements. Error is defined as the difference between temperatures measured by a Campbell Scientific research grade ultrafine-wire thermocouple and a variety of loggers (see text). As an indication of the effect size being measured, the RMS difference between the ultrafine-wire thermocouple measurement and estimates from coarse-gridded ERA5 data are also shown (right-hand column).

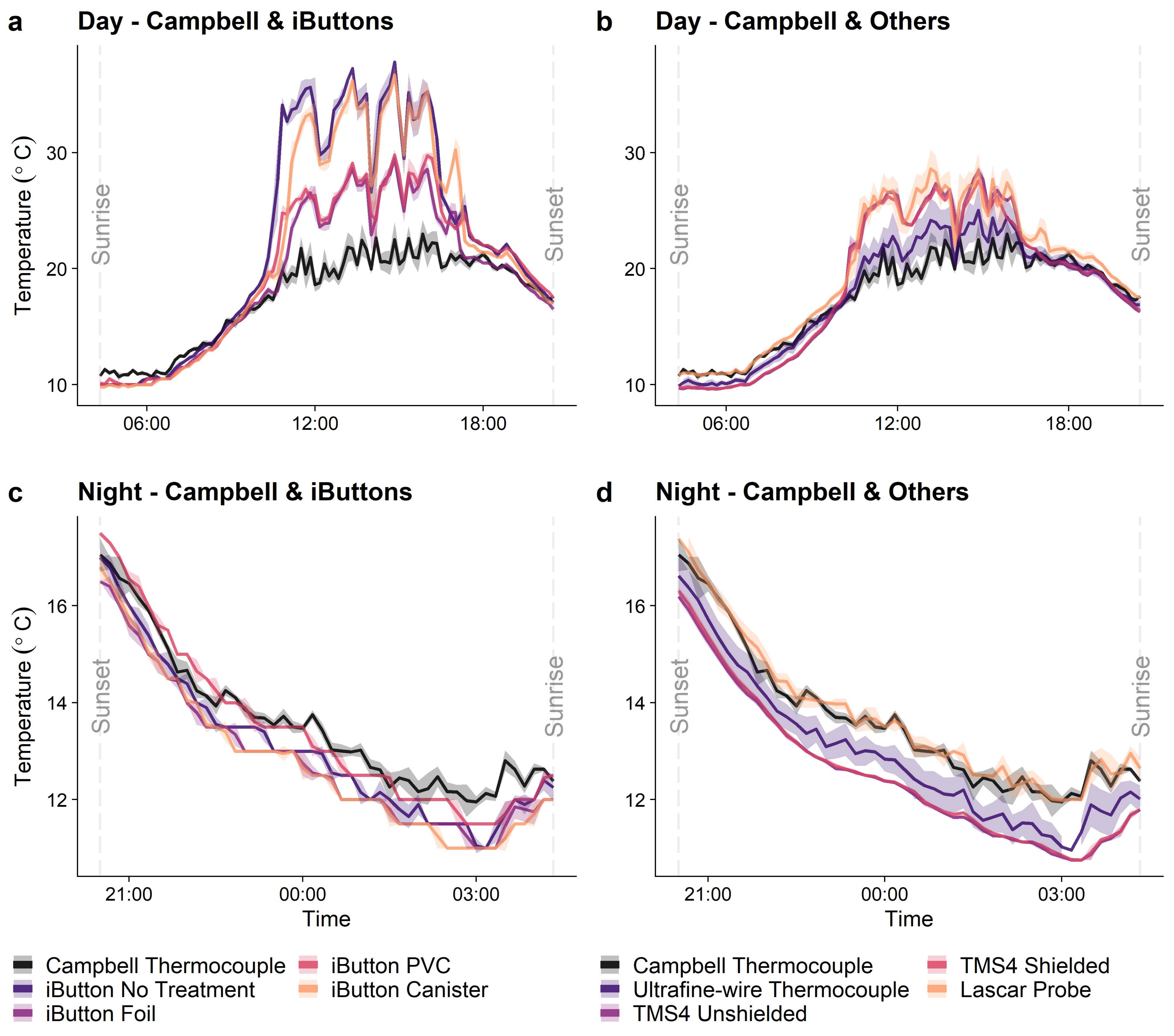
	Consumer-grade u;trafine-wire thermocouple	Standard Lascar thermocouple	Button (unshielded)	iButton (Foil)	iButton (PVC tube)	iButton (transluscent film canister)	TMS4 datalogger (Unshielded)	TMS4 datalogger (Shielded)	RMS difference from coarse-gridded data
Daytime RMS error	1.16	3.6	8.26	4.21	3.87	7.72	3.19	3.24	1.73
Daytime max. error	2.89	7.53	15.52	8.89	8.71	15.17	8.47	9.02	3.87
Night-time RMS error	0.27	0.31	0.57	1.51	1.16	0.93	1.2	1.23	1.00
Night-time max. error	0.49	0.85	1.15	4.47	3.56	1.38	1.6	2.94	2.57
Overall RMS error	0.93	3.40	6.53	3.47	3.16	6.12	2.65	2.67	1.50
Overall max. error	2.89	7.53	15.52	8.89	8.71	15.17	8.47	9.07	3.87

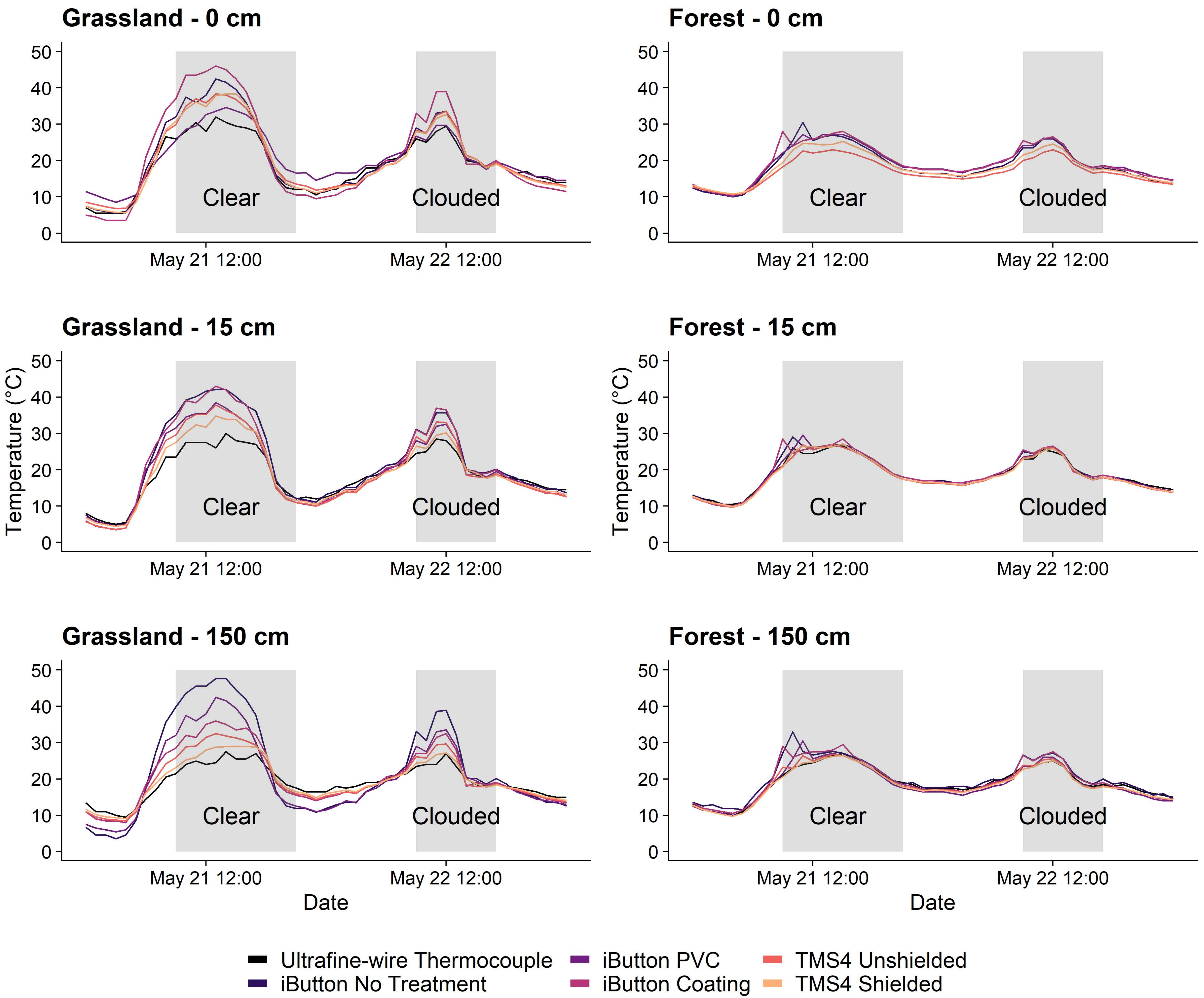
Table 4. Experiment 2. Root-mean-square (RMS) and maximum (in brackets) error of hourly temperature measurements at 0 cm, 15 cm and 150 cm above ground. Error is defined as the difference between temperatures measured using the 0.08 mm Type K thermocouples and those measured using TMS4 datalogger and iButton thermochrons at the same height. As an indication of the effect size being measured, the RMS (and maximum) difference from thermocouple temperatures measurements at 150 cm in the open grassland area, best representing the reference air temperature that would be measured by a weather station, are also shown (right-hand column).

	iButton (unhoused)	iButton (PVC pipe)	iButton (plastic coated)	TMS (unshielded)	TMS (shielded)	Difference from macroclimate
Grassland (0 cm)	3.84 (14.50)	2.14 (7.02)	6.29 (18.50)	3.13 (12.25)	2.98 (10.94)	3.24 (9.50)
Grassland (15 cm)	5.76 (16.65)	4.01 (14.50)	6.14 (17.00)	3.55 (11.94)	2.19 (8.81)	2.40 (8.00)
Grassland (150 cm)	9.17 (25.69)	6.14 (19.50)	3.90 (11.50)	2.57 (8.50)	1.98 (4.44)	--
Forest (0 cm)	1.01 (9.00)	1.07 (6.13)	1.10 (5.50)	1.53 (5.50)	0.93 (4.00)	1.21 (4.50)
Forest (15 cm)	1.26 (13.5)	0.79 (5.50)	1.23 (13.00)	0.79 (4.38)	0.67 (3.62)	1.02 (4.00)
Forest (150 cm)	2.13 (17.94)	1.11 (7.00)	1.80 (17.50)	0.85 (5.75)	0.75 (2.75)	1.00 (4.00)

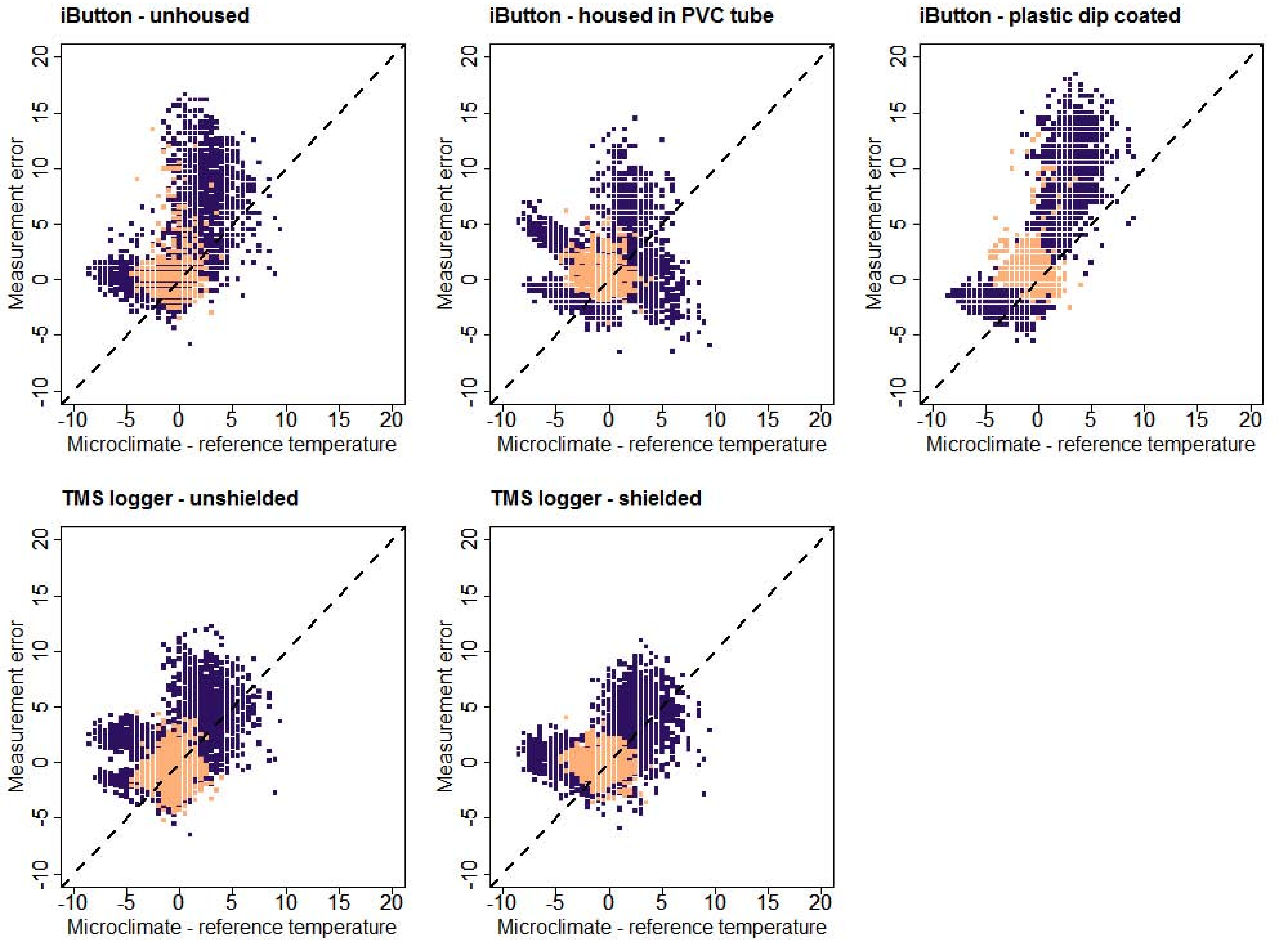
Table 5. Experiment 3. Root-mean-square (RMS) and maximum error of daily and monthly minimum, mean and maximum temperatures obtained in an open field at 2 m above ground. Error is defined as the difference between temperatures obtained at 150 cm above ground using a Lascar ELUSB-1 logger and two different shield types with those obtained by an adjacent official synoptic weather station. For comparison, differences between temperatures measured at the open site and those measured at <1 km distance in a deciduous forest are shown (grey columns).

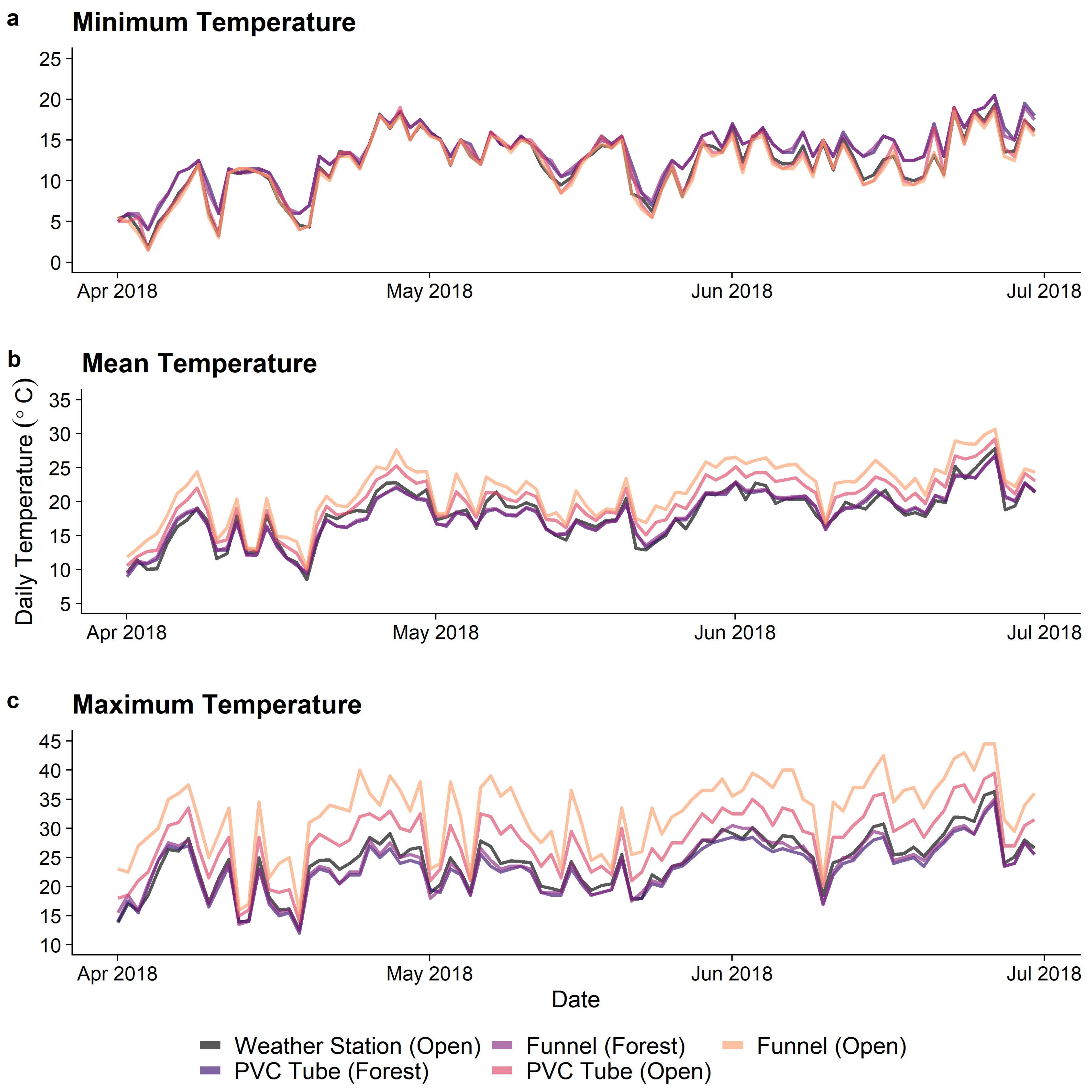
	PVC tube shield				Funnel shield			
	RMS Error	RMS difference	Max. error	Max. difference	RMS error	RMS difference	Max. error	Max. difference
Daily								
Minimum temperature	0.79	1.35	7.34	4.00	0.58	1.47	3.59	5.50
Mean temperature	1.48	1.55	4.74	3.37	2.11	1.98	5.66	5.62
Maximum temperature	3.50	4.38	12.86	13.50	6.47	5.95	14.63	17.5
Monthly								
Minimum temperature	1.36	1.94	5.34	3.50	0.93	1.97	3.93	4.00
Mean temperature	1.21	1.41	2.25	2.20	1.91	1.84	3.96	3.79


a
Day - Campbell & iButtons
b
Day - Campbell & Others
c
Night - Campbell & iButtons
d
Night - Campbell & Others
Temperature (° C)
Sunrise
Sunset
06:00
12:00
18:00
21:00
00:00
03:00
Time
Campbell Thermocouple
iButton No Treatment
iButton Foil
iButton PVC
iButton Canister
Ultrafine-wire Thermocouple
TMS4 Unshielded
TMS4 Shielded
Lascar Probe



Grassland - 0 cm
Forest - 0 cm
Grassland - 15 cm
Forest - 15 cm
Grassland - 150 cm
Forest - 150 cm
Clear
Clouded
Temperature (°C)
Date
May 21 12:00
May 22 12:00
0
10
20
30
40
50
Ultrafine-wire Thermocouple
iButton No Treatment
iButton PVC
iButton Coating
TMS4 Unshielded
TMS4 Shielded


iButton - unhoused
iButton - housed in PVC tube
iButton - plastic dip coated
TMS logger - unshielded
TMS logger - shielded
Measurement error
Microclimate - reference temperature
-10
-5
0
5
10
15
20


a
Minimum Temperature
b
Mean Temperature
c
Maximum Temperature
Daily Temperature (°C)
Apr 2018
May 2018
Jun 2018
Jul 2018
Date
Weather Station (Open)
PVC Tube (Forest)
Funnel (Forest)
PVC Tube (Open)
Funnel (Open)