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Fundamental Sensor Response Time Limitations of Practical Air Temperature Measurement

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Key Points:

- Direct determinations of response times of shielded (Stevenson screen) thermometers under natural ventilation are reported
- In-screen response times to air temperature changes improve for smaller sensors, but still reach 10–20 min under calm conditions
- Diurnal temperature range is underestimated by 0.2°C for a 4 mm in-screen sensor, due mainly to underestimated daily temperature maxima

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Air temperature measurements in naturally ventilated thermometer screens underpin the instrumental climate record. Increasing automation is, however, revealing limitations. One is through thermometer time response, especially in light winds or calm conditions, often at the daily temperature minimum. The exponential time response τ_{63} for thermometers enclosed within a Stevenson screen is a key parameter, but poorly known. Here, τ_{63} is evaluated in a practical experimental situation against the World Meteorological Organization (WMO)'s recommended sensor $\tau_{63} \leq 20$ s. We find τ_{63} increases with sensor diameter d, with only a $d = 2$ mm sensor meeting WMO expectations, even then requiring ambient wind speeds ≥ 3 ms^{-1}. Typical $d = 4$ mm sensors never meet the criterion when either force- or naturally ventilated, with $\tau_{63} \geq 20$ mins in a naturally ventilated arrangement under calm conditions. Inadequate τ_{63} will lead to underestimation of the diurnal temperature range or other local measures derived from daily temperature maxima and minima.

Plain Language Summary The small white slatted boxes containing thermometers for air temperature measurements are a familiar sight, implementing what is effectively the standard method used globally for temperature measurement The slats allow air from outside the box to pass over the thermometers, which generally works well as long as the wind is blowing. However, occasionally, when the wind is light or calm, the thermometers become less responsive, taking longer to register air temperature changes. Our experiment measured thermometer response times in a real field situation, and found that, in light winds, the response time could be greater than 20 min. This would mean that maximum and minimum air temperatures would not be fully reached and properly registered. Smaller temperature sensors were found to respond more rapidly, but remain prone to variations in natural ventilation.

1. Introduction

Air temperature measurements form the backbone of the climate record, traditionally implemented practically using porous louvered boxes (Stevenson, 1864)—known as screens, shields or shelters—to protect thermometers from direct sunlight whilst allowing limited exchange of air. Although extensively evaluated when introduced and regularly since (Chandler, 1964; Margary, 1924), modern automated measurements now allow detailed assessment of the limitations of these practical methods, such as an effect of screen size (Buisan et al., 2015), and the long appreciated (Aitken, 1884) limitation of variable or poor natural ventilation. This can lead to anomalous radiative heating or cooling, with measurable effects upon recorded daily maximum and minimum temperatures (Harrison & Burt, 2024). Another important deficiency arises from the finite time response, which underlies all thermometer measurements. Sensor response time is conventionally characterized by the exponential time constant τ_{63}, that is, the time to register $\left(1 - e^{-1}\right) \approx 63\%$ of a step change. Theory indicates that τ_{63} is proportional to sensor diameter and inversely proportional to ventilation rate (Burt & de Podesta, 2020).

With long sensor response times, the sensitivity to temperature transients typical of daytime boundary layer flow is reduced and daily extreme values are damped. This could, for example, lead to underestimation or even omission of a brief daily temperature maximum, especially on still and sunny days. Insufficient (or variable) thermometer time response is therefore a potentially widespread cause of air temperature inaccuracy, and a new method for rigorous characterization under field conditions is pursued here to assess the practical significance.

2. Operational Context

Rather than specifying a sensor design, the World Meteorological Organization (WMO) advises (World Meteorological Organisation, 2023) that a sensor is chosen to provide $\tau_{63} \leq 20$ s. Such a τ_{63} has some limitations for

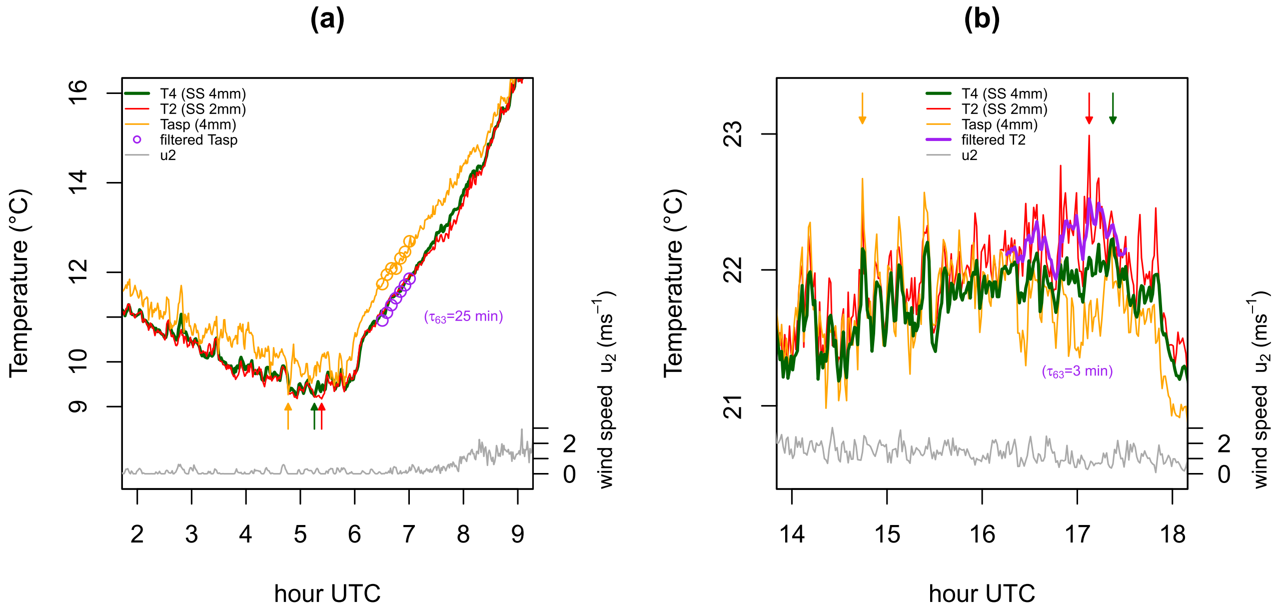

Figure 1. Examples of measured air temperatures around (a) daily minimum (near dawn, 19 August 2024) and (b) daily maximum (afternoon, 20 June 2024). Temperatures were measured with 4 mm (T_4, green) and 2 mm (T_2, red) PRTs within a Stevenson screen (SS) and a 4 mm sensor (orange) within a nearby aspirated shield T_{asp}; occurrence of daily minimum and maximum values are shown by arrows. The nearby 2 m wind speed u_2 is shown on the RH axis. Purple points and lines show the effect of applying an exponential moving average filter to (a) the aspirated (T_{asp}) sensor data and (b) the T_2 sensor data.

daily minima and maxima (Lin & Hubbard, 2008) but is consistent with averaging over 1 min periods, as 95% of a step change is registered after 3 τ_{63}. Unfortunately, these expectations are unlikely to be realized in practice, as, even in well-ventilated circumstances such as laboratory tests, standard liquid-in-glass (LiG) spherical bulb thermometers have $\tau_{63} \sim 50$ s (HMSO, 1981) and typical platinum resistance thermometers (PRTs) (Foken & Bange, 2021) have $\tau_{63} \sim 30$ s.

LiG thermometers are increasingly being replaced with PRT sensors, with associated improved manufacturing tolerances. Some rapid PRT sensors are becoming available (Burt & Baker, 2025). However, enclosure of sensors within a thermometer screen will dominate and lengthen the time response further beyond that of solely the sensor (Bryant, 1968), which is readily apparent through comparison with a faster thermometer (Harrison & Pedder, 2001). Few previous studies have examined the combined screen and sensor time response under field conditions, such as through eclipse-induced changes (Langlo, 1945; Peñaloza-Murillo et al., 2022), or variations in minimum temperature times (Harrison, 2011).

Here, high resolution continuous recording PRTs of varying diameters located within the Reading University Atmospheric Observatory (RUAO) are used to investigate underlying factors influencing the sensor time response effects.

3. Time Response Experiments

Individually calibrated PRTs of 2, 3, and 4 mm diameter (respectively, hereafter referred to as T_2, T_3, T_4) were installed in a large plastic Stevenson screen (SS), alongside a force-ventilated (aspirated) plastic shield (AS) containing a 4 mm diameter PRT, used as a temperature reference (Harrison & Burt, 2021), T_{asp} (see Figures S1–S4 in Supporting Information S1). The aspirated shield draws air over the sensor at a speed of ~5 m s^{-1}. Along with wind speed values from a nearby cup anemometer at 2 m above ground, u_2, all four PRT sensors were sampled at 1 Hz, with data averaged in each UTC minute.

Figure 1 provides example measurements, drawn from our data set (Harrison & Burt, 2025). Figure 1a data was obtained around a daily temperature minimum near dawn on a day with negligible wind (19 August 2024). The times of the minimum temperatures in the different sensors differ by about 40 min (at 0447 UTC, 0516 UTC, and 0524 UTC for T_{asp}, T_4, and T_2 respectively), followed by a consistent difference during the steady temperature rise between 06 UTC and 08 UTC, T_2 and T_4 reaching the instantaneous T_{asp} only about 25 min later. As τ_{63} can alternatively be interpreted, during steady temperature changes, as the thermometer delay (HMSO, 1981), the lag provides an indication of the time response. This can be confirmed by applying an exponential moving average (EMA) filter to smooth the T_{asp} values. In this approach, smoothed values s_n are generated successively from raw samples y_n by

$$s_n = \alpha y_n + (1 - \alpha) s_{n-1}, \quad (1)$$

where

$$\alpha = 1 - \exp\left(-\frac{1}{\tau}\right), \quad (2)$$

for τ the filter time constant (see also Text M1 in Supporting Information S1). The observed lagged response of T_2 and T_4 is replicated if a filter parameter of $\tau = 25$ min is used.

Figure 1b shows a daily temperature maximum on a sunny afternoon during light winds (20 June 2024), with the different sensors recording maximum temperatures of 22.7°C (T_{asp}, at 1445 UTC), 23.0°C (T_2, 1708 UTC) and 22.2°C (T_4, 1723 UTC). Different responses in T_2 and T_4, are again apparent, with a similar qualitative variation to T_4 obtained by EMA filtering of T_2 with $\tau = 3$ min. Beyond the in-screen sensor differences, there is also a temperature offset with T_{asp}. This seems likely to result from heterogeneous radiative heating of the SS (Bell et al., 2022; Yang & Liu, 2017) as investigated previously (Harrison & Burt, 2024), causing warming of the SS sensors compared with the AS sensor, but variably across the SS sensors due to the poor ventilation.

Figure 1 cases demonstrate that, despite being in the same thermometer screen, sensors of different sizes can record different maximum and minimum temperatures at different times, especially in light wind or calm conditions. The combined system τ_{63} is far longer than the WMO expectation for an individual sensor, which motivates further investigation of in-screen thermometer time responses.

4. Results

4.1. Time Response

Time responses of 2, 3, and 4 mm diameter PRT sensors were first evaluated in laboratory experiments using a step change method (Burt & de Podesta, 2020). Figure 2a shows the findings, with τ_{63} decreasing with diminishing sensor size, but greatly increasing for all sizes at low ventilation rates. These time constants are comparable to those for other typically used temperature sensors (Benbow et al., 2018).

The different size sensors were installed in the SS with a fast response fine wire thermometer mounted nearby as a reference (see Figure S2 in Supporting Information S1), synchronously sampled with the other sensors at 1 s. The time response of this fine wire PRT (fwPRT) design (Harrison & Pedder, 2001), has previously been found in a step change experiment as $\tau_{63} = 40$ ms, with a 50 μA excitation current used to minimize self-heating (Harrison & Rogers, 2006). In a calibration experiment, τ_{63} was determined for the AS sensor by applying the EMA filtering of Equation 1 to the adjacent fwPRT temperatures. This used daily data obtained between 6 September 2024 and 26 February 2025 (see Methods 1 in Supporting Information S1).

The main experiment on sensor time response comparison with the fwPRT ran from 6 September 2024 to 7 September 2025, spanning a temperature range −6.5°C to 32.8°C which is typical of the site. Local rates of change of each sensor's temperature were compared, using the relative time constant method (Tagawa & Ohta, 1997) (see Methods 2 in Supporting Information S1). 20 s averages were used for this, to allow smaller and short fluctuations to be included. Figure 2b presents the results, in which the τ_{63} values found for T_{asp} and the screen-enclosed T_2, T_3, and T_4 are binned by wind speed u_2. A long response time is evident in the SS sensors at low wind speeds, but the SS sensor response times become more similar to that of the AS sensor as the wind speed increases.

Beyond the reduction of τ_{63} with increasing ventilation, several other features are apparent from Figure 2. Firstly, the sensors responded far more rapidly in the laboratory (Figure 2a) than when deployed in field conditions within the SS. This is consistent with the independent observation of much reduced sensor ventilation speed within a

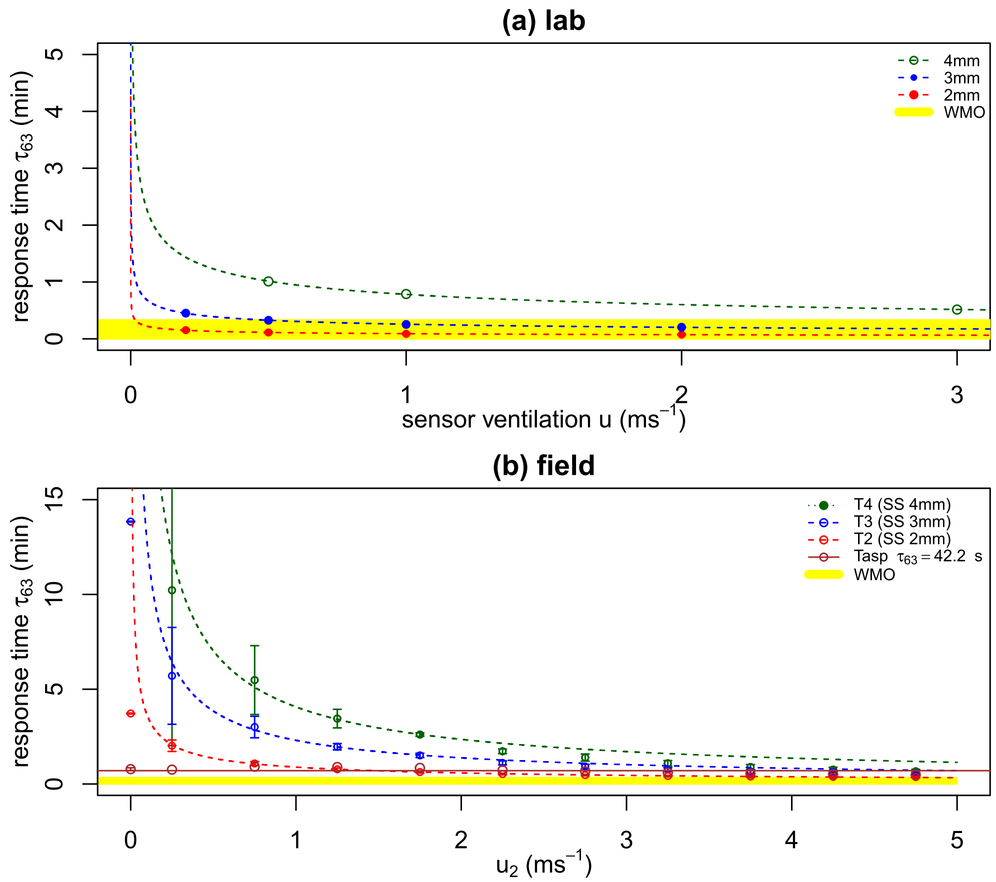

Figure 2. Response times of 2, 3, and 4 mm diameter temperature sensors, measured in (a) the laboratory over a range of ventilations (Burt & de Podesta, 2020) and (b) field conditions within a Stevenson screen (SS), for a range of wind speeds at 2 m (u_2). The field measurements are referenced to a nearby aspirated 4 mm sensor, for which τ_{63} was found separately as (42.2 ± 3.0) s. In (a) and (b) the yellow region marks the WMO-advised sensor time response. The dashed lines are weighted least squares fits of the form $\tau = Au^n$.

thermometer screen, by up to a factor of 10 compared with the external wind speed (Burt, 2022). Secondly, ordering of τ_{63} by size is retained, so that the smallest sensor within the SS responds fastest, that is, having the smallest τ_{63}. Thirdly, under light or calm winds, the combined τ_{63} for a PRT within screen, can become tens of minutes, as already inferred from the observations presented in Figure 1a. Fourthly, if the WMO sensor expectation of $\tau_{63} \leq 20$ s is considered as a benchmark for the screen-sensor system, only the smallest sensor (2 mm diameter) would allow the overall system to achieve this, even so requiring modest wind speeds ($u_2 > 3$ ms^{-1}). Finally, the AS time response is invariant with external wind speed as would be expected, which provides confidence as the same methodology is applied to the SS sensors. The AS response with a 4 mm sensor remains, nevertheless, consistently outside the WMO expectation.

4.2. Observed Limitations of Finite Time Response

The time response variation will lead to different sizes of sensors in the same screen under the same conditions providing different instantaneous temperatures, which may also influence some derived climatological summary properties.

Including additional data before the fWPRT was installed (from 23 March 2023, 899 days' data), the 2 and 4 mm SS sensors are compared in Figure 3a. The Diurnal Temperature Range (DTR) shows a much wider distribution (black lines) than that for the daily mean temperatures (wheat-colored bars), the latter essentially representing the calibration differences. The difference in the DTR is skewed to larger values, indicating that a wider range of temperature is observed by the smaller sensor compared to the larger sensor. This is consistent with an enhanced

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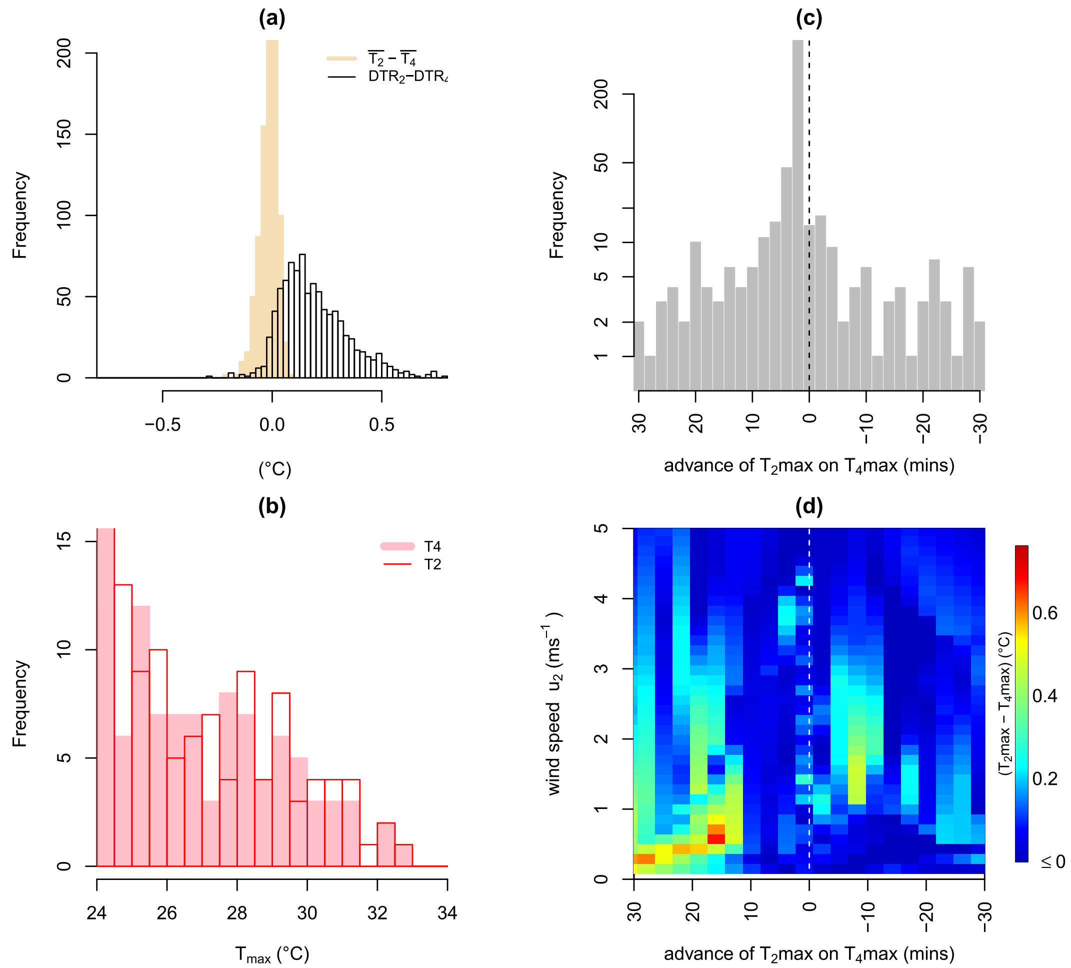

Figure 3. (a) Comparison of 2 and 4 mm sensors (T_2 and T_4), showing differences of mean values (wheat-colored distribution) and diurnal temperature ranges (DTR, black lines). (b) Differences in the occurrence frequency of extreme value temperatures in the data set, measured by T_2 (red bars) and T_4 (pink bars) sensors. (c) Advance of the T_2 maximum time compared with the T_4 maximum. (d) Differences between the T_2 and T_4 maxima, plotted against wind speed and the advance of the T_2 maximum.

time response capturing more, and greater, fluctuations, although days with a large DTR are also more likely to experience rapid temperature changes than days with a smaller DTR.

Figure 3b explores this further, by comparing the upper ranges of the daily maximum temperatures (T_{max}) for the two sensors. For $T_{max} > 30°C$, 16 values were provided by the 2 mm sensor compared with 12 by the 4 mm one. Their differences ($T_{2max} - T_{4max}$) between $T_{4max} > 25°C$ and $20°C > T_{4max} > 25°C$ have different medians, from different distributions, using Mann-Whitney and Kolmogorov-Smirnov tests, ($p < 10^{-6}$ and $p < 10^{-5}$ respectively).

Timing of the temperature maxima measurements is considered in Figures 3c and 3d. Figure 3c shows the differences in the daily T_{max} times between the 2 and 4 mm sensors. In general, more 2 mm sensor daily temperature maxima occur before the 4 mm sensor maxima (number of values before, $N = 411$), than after ($N = 156$), with a mean advance of 6.7 min, however the sensor time response differences identified will cause other asymmetric responses under varying meteorological circumstances. The actual T_{max} values obtained are explored further in Figure 3d, which compares the 2 and 4 mm sensor differences with wind speed. This shows that T_{2max} exceeds T_{4max} at low wind speeds ($u_2 < 1$ ms^{-1}), for temperature maxima that occur 20–30 min earlier for the smaller sensor.

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Table 1
Summary Quantities From Daily Values Using the Aspirated Shield Sensor and the Different-Sized Sensors in the Stevenson Screen (SS)

Sensor	Designation	Median daily min (°C)	Median daily max (°C)	Median of DTR (°C)	Median of daily bimeans (°C)	Median of daily full arithmetic means (°C)
4 mm asp	T_{asp}	8.26	16.83	8.70	12.68	12.55
4 mm SS	T_4	8.25	16.76	8.50	12.58	12.44
3 mm SS	T_3	8.25	16.96	8.69	12.66	12.48
2 mm SS	T_2	8.17	16.88	8.69	12.61	12.41

5. Discussion

These results provide some of the very few in situ field determinations of sensor response time within a naturally ventilated Stevenson screen. Both the sensor size and local wind speeds affect the response time, which can propagate forward into both the values of temperature maxima and minima observed, and their times of occurrence.

Temperature maxima or minima values that are displaced in time will represent different micrometeorological circumstances. These fundamental effects arising from poor ventilation will be greatest over land at night around the temperature minimum (Harrison, 2010), but a damped thermometer response will also cause some daily maximum temperatures to be underestimated in light wind conditions, potentially reducing the level of extreme maximum temperatures.

Although this work primarily investigates the sensor time response, Table 1 provides some broader context, through summarizing quantities derived from daily values for the 899 days with all the SS sensors operating. Only differences between the quantities are considered, as the absolute values are influenced by partial sampling of the years concerned (Median values are used to reduce effects from outliers).

Table 1 shows that the median DTR is reduced by 0.2°C for the 4 mm SS sensor, compared with the 4 mm aspirated shield sensor with smaller DTR reductions for the 3 and 2 mm sensors. These are consistent with size-dependent time response effects, with the SS T4 DTR reduction influenced more by the daily temperature maxima than minima.

Daily maxima and minima are also sometimes used together to estimate the daily average temperature. The last two columns in Table 1 compare the daily mean temperature estimated by averaging just the daily maximum and minimum (i.e., the daily bimean) and the full daily arithmetic mean found using all 1 min samples, showing consistency to 0.2°C.

6. Conclusion

The effects investigated do not cast doubt on the observed atmospheric warming recorded using existing standard technologies, as the globally established changes are far larger than the uncertainties considered here. For example, the median reduction in DTR between aspirated and naturally-ventilated thermometers is 0.2°C, which is relatively small. However, the frequency and magnitude of extremes can be used as indicators of local rates of change. Hence, establishing measuring consistency by removing ventilation variability associated with naturally-ventilated thermometer screens is important, for example, through more widespread use of small sensors deployed in aspirated thermometer shields.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data and analysis code are available at Harrison and Burt (2025).

Acknowledgments
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References

Aitken, J. (1884). Thermometer screens. *Proceedings of the Royal Society of Edinburgh*, *12*, 661–696. https://doi.org/10.1017/s0370164600001243

Bell, S., Bevilacqua, L. G., Pearce, J. V., & Underwood, R. J. (2022). Towards radiatively immune thermometry in weather stations. In *The 2022 WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO-2022)*. Retrieved from https://wmoomm.sharepoint.com/:b:/s/wmocpdb/EYazHh9QE0VKl5CcFeEeB9ABrXzTWWW7fPwgBBetnfIe1Q?e=7StTao

Benbow, D., Dollery, I., & Warne, J. (2018). Instrument Test Report 714: Response times of surface thermometers. Bureau of Meteorology.

Bryant, D. (1968). An investigation into the response of thermometer screens—The effect of wind speed on the lag time. *Meteorological Magazine*, *97*, 183–186.

Buisan, S. T., Azorin-Molina, C., & Jimenez, Y. (2015). Impact of two different sized Stevenson screens on air temperature measurements. *International Journal of Climatology*, *35*(14), 4408–4416. https://doi.org/10.1002/joc.4287

Burt, S. D. (2022). Measurements of natural airflow within a Stevenson screen and its influence on air temperature and humidity records. *Geoscientific Instrumentation, Methods and Data Systems*, *11*(2), 263–277. https://doi.org/10.5194/gi-11-263-2022

Burt, S. D., & Baker, D. V. (2025). Improved time constant of a newly released air temperature sensor and its implications. *Quarterly Journal of the Royal Meteorological Society*, *151*(771), e4996. https://doi.org/10.1002/qj.4996

Burt, S. D., & de Podesta, M. (2020). Response times of meteorological air temperature sensors. *Quarterly Journal of the Royal Meteorological Society*, *146*(731), 2789–2800. https://doi.org/10.1002/qj.3817

Chandler, T. J. (1964). North-wall and Stevenson screen temperatures at Kew Observatory. *Quarterly Journal of the Royal Meteorological Society*, *90*(385), 332–333. https://doi.org/10.1002/qj.49709038514

Foken, T., & Bange, J. (2021). Temperature sensors. In T. Foken (Ed.), *Handbook of atmospheric measurements* (pp. 183–208). Springer Cham. Switzerland. https://doi.org/10.1007/978-3-030-52171-4_7

Harrison, R. G. (2010). Natural ventilation effects on temperatures within Stevenson screens. *Quarterly Journal of the Royal Meteorological Society*, *136*(646), 253–259. https://doi.org/10.1002/qj.537

Harrison, R. G. (2011). Lag-time effects on a naturally ventilated large thermometer screen. *Quarterly Journal of the Royal Meteorological Society*, *137*(655), 402–408. https://doi.org/10.1002/qj.745

Harrison, R. G., & Burt, S. D. (2021). Quantifying uncertainties in climate data: Measurement limitations of naturally ventilated thermometer screens. *Environmental Research Communications*, *3*(6), 061005. https://doi.org/10.1088/2515-7620/AC0D0B

Harrison, R. G., & Burt, S. D. (2024). Accuracy of daily extreme air temperatures under natural variations in thermometer screen ventilation. *Atmospheric Science Letters*, *25*(10), e1256. https://doi.org/10.1002/asl.1256

Harrison, R. G., & Burt, S. D. (2025). Thermometer time response investigations [Dataset]. *Figshare*. https://doi.org/10.6084/m9.figshare.29271101

Harrison, R. G., & Pedder, M. A. (2001). Fine wire thermometer for air temperature measurement. *Review of Scientific Instruments*, *72*(2), 1539–1541. https://doi.org/10.1063/1.1336819

Harrison, R. G., & Rogers, G. W. (2006). Fine wire resistance thermometer amplifier for atmospheric measurements. *Review of Scientific Instruments*, *77*(11), 116112. https://doi.org/10.1063/1.2400013

HMSO. (1981). *Handbook of meteorological instruments: Measurement of temperature* (2nd ed.). Meteorological Office.

Langlo, K. (1945). The effects of the solar eclipse of July 1945 on the air temperature and an examination of the lag of a thermometer exposed in a screen. *Meteorol Ann Oslo*, *3*, 59–74.

Lin, X., & Hubbard, K. G. (2008). What are daily maximum and minimum temperatures in observed climatology? *International Journal of Climatology*, *28*(3), 283–294. https://doi.org/10.1002/joc.1536

Margary, I. D. (1924). Glaisher stand versus Stevenson screen. A comparison of forty years' observations of maximum and minimum temperature as recorded in both screens at Camden Square, London. *Quarterly Journal of the Royal Meteorological Society*, *50*(211), 209–226. https://doi.org/10.1002/qj.49705021109

Peñaloza-Murillo, M. A., Roman, M., Pasachoff, J., & Elmhamdi, A. (2022). An empirical study of near-surface air temperature time lags and delay function during the longest total solar eclipse of the 21st century at Tianhuangping (Zhejiang), China, under cloudy conditions. *Meteorologische Zeitschrift*, *31*(3), 243–261. https://doi.org/10.1127/metz/2022/1094

Stevenson, T. (1864). New description of box for holding thermometers. *Journal of the Scottish Meteorological Society*, *1*, 122.

Tagawa, M., & Ohta, Y. (1997). Two-thermocouple probe for fluctuating temperature measurement in combustion—Rational estimation of mean and fluctuating time constants. *Combustion and Flame*, *109*(4), 549–560. https://doi.org/10.1016/S0010-2180(97)00044-8

World Meteorological Organisation. (2023). WMO No.8—Guide to meteorological instruments and methods of observation (CIMO guide). In *Volume I: Measurement of meteorological variables*. Geneva Retrieved from https://library.wmo.int/idurl/4/68695

Yang, J., & Liu, Q. Q. (2017). A temperature error correction method for a thermometer screen. *Acta Physica Polonica A*, *132*(4), 1301–1305. https://doi.org/10.12693/APhysPolA.132.1301