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RESEARCH ARTICLE

Improved time constant of a newly released air temperature sensor and its implications

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Abstract

The World Meteorological Organization (WMO), National Oceanic and Atmospheric Administration, and other organizations provide guidance on expected response time for sensors used to measure air temperatures intended for meteorological applications. Quantified as the sensor time constant (the time it takes for a sensor to reflect some percentage of a step change), recommendations differ somewhat depending on the organization. For instance, the WMO specifies the 63% time constant should be ≤20 s, although, crucially, the organization does not state the air flow velocity at which this time constant should be achieved. Recent independent tests at two laboratory facilities (initially the University of Reading, United Kingdom, and subsequently at Campbell Scientific, Logan, Utah, United States) were undertaken to determine time constants of a range of commercially available platinum resistance thermometer sensors. Results showed that many sensors fell far short of the WMO specification at airflow rates typical of naturally ventilated thermometer screens or radiation shields ($1\ \mathrm{m \cdot s^{-1}}$ or lower). In contrast, a recently released platinum resistance thermometer sensor from Campbell Scientific was shown to meet both specifications, even at airflow rates within a laboratory wind tunnel as low as $0.2\ \mathrm{m \cdot s^{-1}}$, which is more typical of naturally ventilated thermometer screens or radiation shields. Across multiple sensors and repeated test runs, the new sensor's 63% response time averaged 10.7 s (standard deviation 0.5 s) at an airflow of $1\ \mathrm{m \cdot s^{-1}}$ and 17.1 s (standard deviation 0.9 s) at $0.2\ \mathrm{m \cdot s^{-1}}$. To our knowledge, this is the first commercially available sensor to attain this WMO specification. However, using or switching to faster-response sensors has important implications for long-term data records, the measurement of extreme temperatures (specifically daily maximum and minimum data), and intersite comparisons. This is compounded by seemingly conflicting recommendations from the WMO regarding sensor time constant versus data processing methods.

KEYWORDS

air temperature, platinum resistance thermometer, response time

1 | INTRODUCTION

Accurate air temperature measurements are critically important in a wide range of scientific, economic, and social contexts. The World Meteorological Organization's (WMO's) Commission for Instruments and Methods of Observation (CIMO) Guide (WMO, 2023) and recent publications based on it (e.g., Burt, 2024) provide guidelines for ensuring consistency in standardized meteorological air temperature records. The adoption of the UN Minamata Convention in 2013 led to statutory limitations on the manufacture and sale of mercury-based instruments, as a result of which mercury-based thermometers have been progressively phased out over the past decade (minamataconvention.org/en; WMO, 2023, section 2.1.4.5). Today, most meteorological temperature measurements are made with platinum resistance thermometers (PRTs). For a more comprehensive overview of historical and current air temperature measurement methods, see Foken (2022, chap. 7).

In addition to the exposure of the sensor itself, the response time of the sensor is a key determinant in both precision and accuracy in all air temperature measurements. A sensor needs to be fast enough to respond quickly to meteorologically relevant variations in air temperature, which typically occur on time-scales of about a minute. However, it should not be overly sensitive to minor fluctuations caused by turbulent air exchange on time-scales of seconds or less, as these fluctuations generally hold little meteorological, climatological, or social significance. The WMO CIMO guide (WMO, 2023, section 2.1.3.3, annex 1.A) recommends a response time of ≤20 s for air temperature measurements, along with guidance on averaging times – specifically, 60 s averages of sub-60 s samples. This article will further discuss both aspects.

1.1 | Response-time theory

The rate of change of a thermometer temperature is given by

$$\frac{dT}{dt} = \frac{T_{\mathrm{air}} - T}{R_{\mathrm{th}}C}, \tag{1}$$

where t is time, T_{air} is the air temperature, T is the thermometer temperature, R_{th} is thermal resistance, and C is the heat capacity of the thermometer; $R_{\mathrm{th}}C$ is known as the time constant, τ.

A thermometer will respond to an instantaneous step change from T_0 to T_1 according to

$$T(t) = T_0 + (T_1 - T_0)\left[1 - \exp\left(-\frac{t}{\tau}\right)\right]. \tag{2}$$

The exponential term approaches zero for t much greater than τ, and T approaches T_1. When $t = \tau$, T will be 63% of the step change $(T_1 - T_0)$, and 95% after 3τ. Note that there is not a standard percentage across manufacturers to report time constant on data sheets (nor even to state the working medium in which the tests were undertaken; e.g., air, water, or other fluids). Therefore, for clarity, we will henceforth refer to this exponential time constant as τ_{63} and assume air as the working medium.

Step changes are uncommon in meteorological air temperature measurements. Instead, the effect of the finite sensor time-constant causes the sensor to lag behind the actual air temperature by

$$T(t) = T_{\mathrm{air}}(t) - \tau_{63}\frac{dT_{\mathrm{air}}}{dt}. \tag{3}$$

For a sensor meeting the CIMO guideline of $\tau_{63} = 20$ s, a 1 K step change of air temperature would result in a temperature measurement error exceeding 0.2 K (the maximum total uncertainty per the CIMO guideline) for just over 30 s following the step change. This error would then reduce to nearly zero after 60 s (i.e., $3\tau_{63}$), which is generally acceptable in most meteorological applications.

However, for sensors with longer time constants (as seen in most sensors examined in this experiment) and during more rapid rates of temperature change, errors exceeding 0.2 K can persist for considerable periods. Under such circumstances, a sensor with $\tau_{63} = 120$ s (typical of many 6 mm PRTs in laboratory tests, as described later herein) would indicate a temperature error of at least 0.2 K for nearly 200 s following a 1 K step change. Without further changes, the error would not reduce to near zero until 360 s (6 min) after the step change, or $3\tau_{63}$. Clearly, sensor errors will both increase and persist for longer with larger step changes. The situation worsens still further when a PRT is sleeved to function as a wet bulb, where "bare PRT" response time can easily be doubled or trebled in typical low-velocity within-screen airflow conditions (Burt, 2022, section 4.3.4). Such short-term changes in air temperature, which are not uncommon in temperate latitudes, can quickly result in significant and semi-persistent errors in derived dew-point and relative humidity calculations.

For a more detailed treatment on response time, see Harrison (2014, section 2.2).

1.2 | Quantifying PRT response times

A series of laboratory tests have been conducted (and continue) to quantify actual response times of typical commercial PRTs used in meteorological applications. Results published in 2020 (Burt & de Podesta, 2020), along with a theoretical analysis based on those findings, determined that the two most important determinants of PRT response time are ventilation speed (airflow) and sensor diameter. This article extends those tests, including additional sensors that have become available since the original study.

Surprisingly, the WMO CIMO guide (WMO, 2023, section 2.1.3.3, annex 1.A) fails to specify the ventilation rate at which the specified time constant applies. Previously, a ventilation rate of 1 $\mathrm{m \cdot s^{-1}}$ has been assumed to be relevant for passively ventilated radiation shelters, such as Stevenson screens and similar shields (Burt & de Podesta, 2020; ISO, 2007). However, a recent 3 month field campaign conducted at the University of Reading Atmospheric Observatory (Burt, 2022) showed that the mean airflow velocity inside a standard Stevenson screen in a research-grade external setting was ~0.2 $\mathrm{m \cdot s^{-1}}$. In fact, airflow within the screen reached 1 $\mathrm{m \cdot s^{-1}}$ or greater for only 0.01% of the observation period. Low ventilation rates inside the screen can significantly impact air temperature measurements, partly due to increased response time, as shown in the following results, and partly due to reduced air exchange with the "true" air temperature outside the screen or shelter.

The background outlined in the previous paragraphs highlights the importance of using fast-response air temperature sensors that meet or exceed WMO's guidance of $\tau_{63} < 20$ s. With this in mind, and following the work of Burt and de Podesta (2020) demonstrating that none of the 25 commercially available third-party PRTs tested in that study met the WMO standard, Campbell Scientific set out to design and manufacture a high-accuracy PRT air temperature sensor for meteorological and climatological applications that would comfortably meet or exceed $\tau_{63} \leq 20$ s. This culminated in the development of the TempVue™ 10 PRT (Figure 1), announced globally in 2023 (hereafter referred to as "the 1.5 mm sensor", reflecting its rod diameter). Given the apparent lack of commercially available WMO-compliant sensors, the purpose of this work is to build on the previous work of Burt and de Podesta and thereby increase awareness of the importance of response time as a factor in sensor selection. More specifically, we had the following objectives:

- To document the parallel laboratory tests undertaken providing objective evidence from a second, independent study demonstrating whether or not the new 1.5 mm sensor and other, more recently available, sensors meet the $\tau_{63} < 20$ s specification recommended by WMO CIMO.
- Perhaps even more importantly, whether this sub-20 s specification is met at airflow rates typical of those in Stevenson-type thermometer screens and their equivalents.

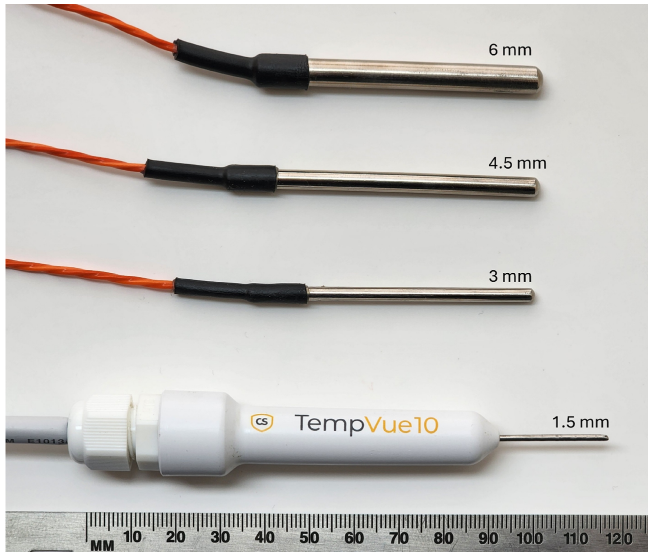

FIGURE 1 Platinum resistance thermometer (PRTs) used in the Logan trials. The 3, 4.5, and 6 mm PRTs are similar in design to those used in Burt and de Podesta (2020). The differing body design on the 1.5 mm PRT is for compatibility with most commonly used radiation shields and to house electronics for a digital version. [Colour figure can be viewed at wileyonlinelibrary.com]

2 | METHODS

2.1 | Data collection

A series of identical laboratory tests were conducted to determine the response times of a variety of commercially available third-party PRTs. The initial experimental laboratory protocol was established at the Department of Meteorology at the University of Reading in the United Kingdom and is detailed in Burt and de Podesta (2020). Since then, further work has been carried out at the University of Reading with additional PRTs that have become available since the initial tests in 2018–2019, as well as examining performance at ventilation speeds down to 0.2 $\mathrm{m \cdot s^{-1}}$. The combined results are summarized in the following section.

The work was later and independently replicated at Campbell Scientific's office in Logan, Utah, United States, using a similar methodology (Figure 2). In the Logan study, the test section of the benchtop wind tunnel used was 80 cm long, 20 cm in cross-section, and equipped with a reference PRT and a hot-wire anemometer. A small heating plate with an aluminium block was positioned next to the wind tunnel to create a repeatable, stable step change by raising the temperature of the test sensor 10–15 K above ambient. An independent PRT was used to monitor the temperature in the block. All sensors were measured with a Campbell Scientific CR1000X data logger, with temperature data from all PRTs logged at 10 Hz. During each trial, the sensor under test was placed in the heater and allowed

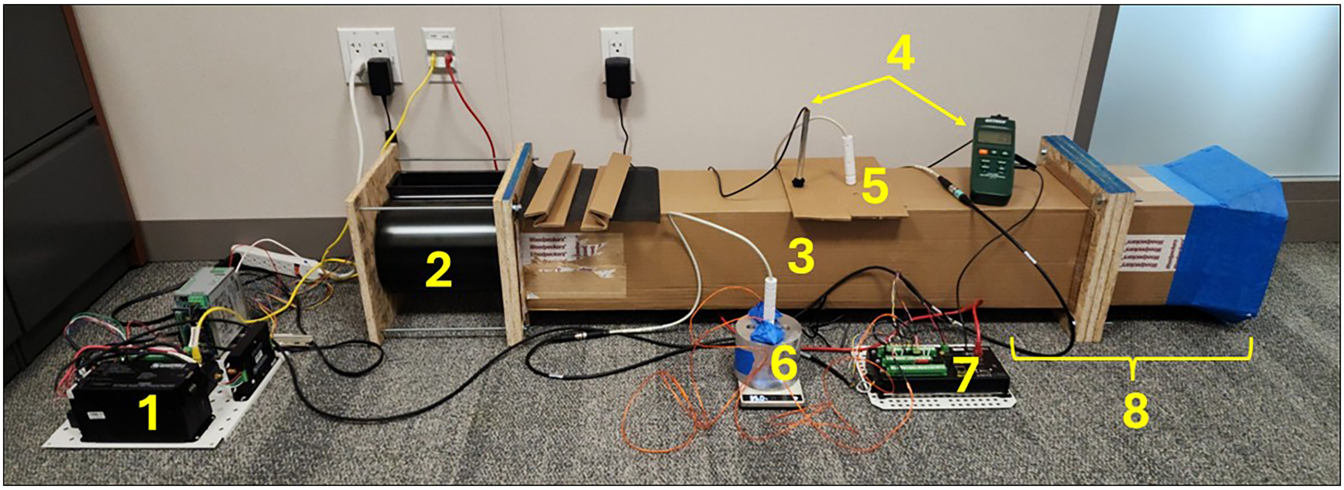

FIGURE 2 Wind tunnel at Campbell Scientific's facilities in Logan, Utah, United States, for the evaluation of platinum resistance thermometer (PRT) response times. The set-up closely replicated the original series of tests made in the Department of Meteorology at the University of Reading, United Kingdom (Burt & de Podesta, 2020). The Logan tunnel test section was 80 cm long, 20 cm in cross-section, and equipped with a reference PRT and hot-wire anemometer. 1. Control and monitoring of the fan. 2. Fan. 3. Test section; air flow from right to left. 4. Hot-wire anemometer. 5. Reference PRT with orifices for sensors-under-test to either side. 6. Heater and aluminium block. 7. Measurement and storage of PRTs and anemometer. 8. Intake section, including screen and tubes to facilitate laminarization and evenness of airflow. [Colour figure can be viewed at wileyonlinelibrary.com]

to equilibrate. Once the measurement had stabilized, the sensor was rapidly transferred to the wind tunnel and allowed to re-equilibrate for a minimum of 15 min to ensure ample time for the sensor to fully settle. The maximum and minimum temperatures from this period were used to define the step change (see Section 2.2). A Campbell Scientific CR6 data logger and SDM-AO4A were used to control wind tunnel airflow rate via voltage regulation and pulse width modulation of the DC fan motor.

The wind tunnel constructed and used at the Reading laboratory differed slightly from that at Logan in cross-section size, length, flow direction relative to the position of the fan (pulling versus pushing air through the test section), and the specific instruments, fan, and fan control used – see Burt and de Podesta (2020) for more details – but the minor changes are not believed to have affected observed experimental outcomes in any significant manner, as explained subsequently.

In the initial experiments in Reading, PRT response times were measured at ventilation speeds between 0.5 and 3.0 $\mathrm{m \cdot s^{-1}}$. These measurements were repeated and then averaged over several runs. More recent tests have extended the lower ventilation speed to 0.2 $\mathrm{m \cdot s^{-1}}$, thus emulating more typical airflow within a Stevenson screen (Burt, 2022), while limiting the upper speed to 2 $\mathrm{m \cdot s^{-1}}$. In the trials undertaken in Logan, ventilation speeds of 0.2, 0.5, 1.0, and 2.0 $\mathrm{m \cdot s^{-1}}$ were used.

To assess whether the slightly different experimental set-ups between the two laboratories produced similar results across a range of PRTs, the trials at Logan included three commercially available PRTs of 3, 4.5, and 6 mm diameter (all 50 mm in length) similar to those previously tested in the UK laboratory (sensor lengths varying between 50 and 100 mm) but from different US-based suppliers. Both sites also independently tested three early production units of the new 1.5 mm diameter, 25 mm long PRTs.

2.2 | Processing and analysis

All tests at both locations set out to determine the sensor response time by measuring the fall in temperature from an elevated value, typically around 35°C, to an equilibrium level sometime later, usually the laboratory room temperature, around 20°C. The time elapsed from the start point (sensor introduced into the wind tunnel) to the point at which 63% of the step change occurred was derived from the sub-second logged temperature data. For example, if the start temperature was 35.0°C and the final equilibrium temperature was 20.0°C, then, by definition, τ_{63} would be the time elapsed from the start to when the temperature had fallen to 63% of the 15 K interval, namely 25.55°C (i.e., 35.0°C minus 15 K × 0.63). Start and end temperatures varied slightly for each run, but there were no specific requirements for starting or ending at particular temperatures; only the time elapsed to the τ_{63} point was evaluated based on the logged sub-second PRT temperature data. An objective algorithm was applied to both sets of trial data to ensure small variations in the decaying exponential asymptote did not cause erroneous results, which was

TABLE 1 Summary results from PRT response time tests, Reading UK and Logan, Utah, USA

Sensor	No. units tested	No. of tests	Response time τ_{63} (SD) (s)						
			$U = 0.2$	0.5	1.0	1.5	2.0	2.5	3.0
Reading									
CS TempVue 10 (1.5 mm)	3	104	**15.9** (0.3)	**12.0** (0.4)	**9.9** (0.4)	**8.7** (0.2)	**7.9** (0.2)	**7.1** (0.5)	
PRT 3 mm (3 mm × 50 mm and 3 mm × 100 mm)	8	142		32.6 (1.4)	25.7 (1.0)	23.3 (0.3)	**18.5** (0.8)		**17.6** (0.6)
PRT 4 mm (4 mm × 75 mm)	3	44		60.6 (1.8)	45.3 (1.8)				30.9 (1.4)
PRT 6 mm (6 mm × 50 mm and 6 mm × 100 mm)	7	153		104.1 (2.3)	82.6 (2.0)	65.4 (1.5)	59.1 (2.3)		54.9 (1.3)
Logan									
CS TempVue 10 (1.5 mm)	3	36	**18.2** (1.5)	**14.6** (1.1)	**11.5** (0.7)		**9.9** (0.8)		
PRT 3 mm × 50 mm	3	27		37.5 (1.6)	28.8 (1.1)		24.7 (1.8)		
PRT 4.5 mm × 50 mm	3	27		67.1 (0.9)	49.9 (0.5)		39.6 (0.7)		
PRT 6 mm × 50 mm	3	27		125.8 (4.2)	89.0 (1.3)		68.4 (1.7)		

Note: Average PRT response times (seconds) for 63% change τ_{63} by sensor size (sheath diameter $d \times$ length L, mm) and for different ventilation rates U, m·s^{-1}, aggregated by sensor size, with standard deviation SD, for both sets of laboratory tests. The number of sensors tested and number of samples for each ventilation rate are also shown. Reading data includes some averages of individual PRT results first published in Burt and de Podesta (2020). Response times τ_{63} sub 20 s are shown in bold.

particularly useful for the fast response time series. This approach was also of benefit in preserving the sharp "elbow" (the start point) in the data when the sensor was moved quickly from the heat source to the wind tunnel.

The laboratory results from the initial Reading laboratory trials were objectively quantified and a physically based model fitted to the data, which identified two key performance variables: sensor diameter and ventilation speed (Burt & de Podesta, 2020). This approach allows testing of hypotheses and inference regarding drivers of the sensor response time, although there are inevitable variations within the dataset due to PRTs being sourced from different manufacturers and inevitable slight variations between and within both sensors and the laboratory tests themselves. It was not deemed necessary to revisit this comprehensive theoretical foundation in the current work.

3 | RESULTS AND DISCUSSION

The results reported in Burt and de Podesta (2020) and from the Logan tests were fundamentally consistent, thus indicating that minor differences between the two sites in laboratory wind tunnel design/construction and analytical technique did not significantly affect experimental results. Both sets of laboratory tests confirmed the expected pattern of increasing time constant with increasing sensor diameter (Table 1, Figure 3). Most of the minor differences can be explained by the fact that, with the exception of the new 1.5 mm sensors, the PRTs tested came from different suppliers, and some degree of variation in composition and construction is to be expected. This was most obvious in the case of the 6 mm PRTs (Table 1, Figure 3).

The results convincingly confirm those of Burt and de Podesta (2020); namely that, with a single exception, none of the 41 commercially available PRTs tested to date met the WMO CIMO specification for <20 s 63% response time at 1 m·s^{-1} airflow. The sole exception was the 1.5 mm PRT, which achieved an average τ_{63} across both sites of 10.7 s (standard deviation, SD, 0.5 s) at 1 m·s^{-1} airflow, and 17.1 s (SD 0.9 s) at 0.2 m·s^{-1}, the latter representing typical airflow within a standard Stevenson screen. These results for the 1.5 mm PRT are the first to be demonstrably within the WMO CIMO specification in independent tests.

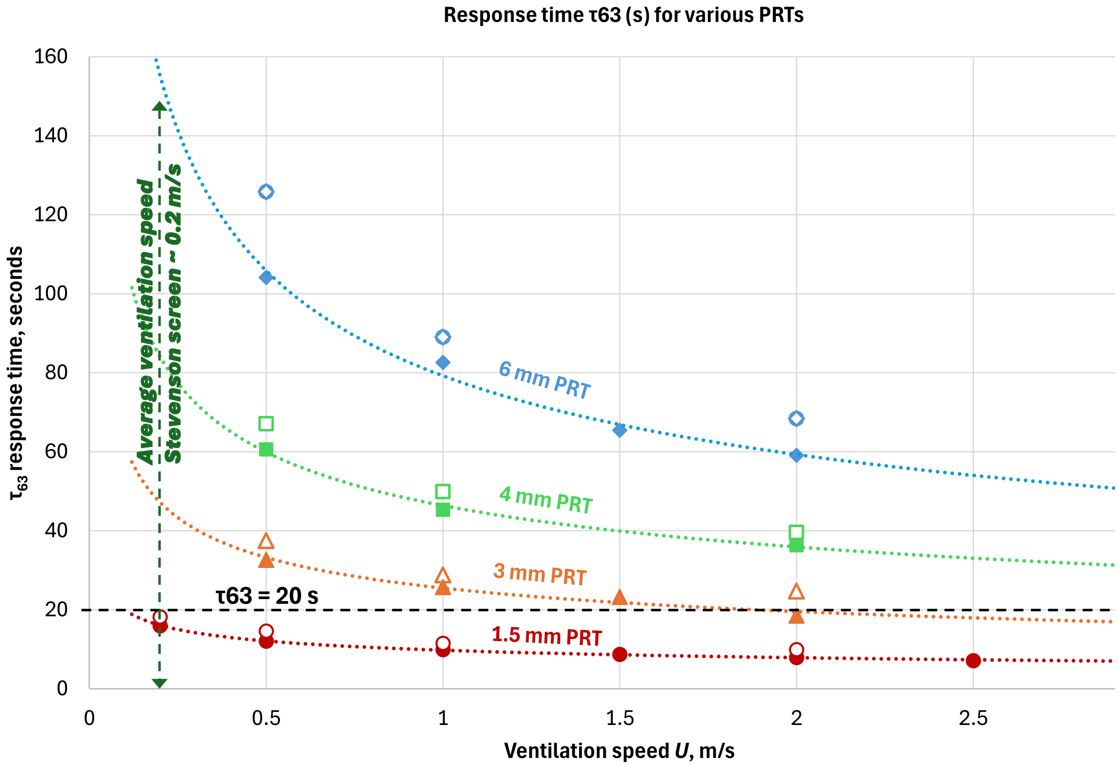

FIGURE 3 The variation of platinum resistance thermometer (PRT) time constant with sensor diameter, by ventilation speed U ($\mathrm{m{\cdot}s^{-1}}$); summarizing sensor categories by diameter—data from Table 1. The World Meteorological Organization's τ_{63} 20 s specification is shown by the horizontal dashed black line. The vertical dashed line highlights the average ventilation speed in a Stevenson screen of $0.2\,\mathrm{m{\cdot}s^{-1}}$ (Burt, 2022). Open symbols are Logan laboratory data, filled symbols are from Reading – both are means within sensor type and ventilation speed. For clarity, power law best-fit curves are also shown for the Reading data only.

The sub-20s τ_{63} result at $0.2\,\mathrm{m{\cdot}s^{-1}}$ airflow is particularly important, due to the near-global standardization of double-louvred Stevenson-type screens for meteorological air temperature measurements. Ignoring for the moment the effect of the thermometer screen/radiation shelter itself upon the combined response time of screen and sensor – an effect that varies with wind speed, but is most significant at surface wind speeds $<2\,\mathrm{m{\cdot}s^{-1}}$ (Harrison, 2010, 2011; Harrison & Burt, 2021, 2024) – it is clear that the introduction of PRTs with τ_{63} times meeting the WMO CIMO guidelines would lead to significant improvements in both consistency and standardization in air temperature measurements.

Given the demonstrable lack of commercially available PRTs that comply with WMO CIMO response time guidelines, it seems almost certain that air temperature sensors at most, if not all, meteorological and climatological stations around the globe currently fall short of WMO recommendations regarding their response time characteristics. This issue is further compounded where combination temperature and relative humidity sensors are utilized, as these instruments are typically even slower to respond to changes in ambient conditions. The situation is also problematic when PRTs are sleeved as wet bulb thermometers. Response times in both of these circumstances are likely to be several minutes. Therefore, we recommend, for both new networks and existing networks that are undergoing upgrades, consideration be given to improved data comparability between air temperature measurements, both in time and space, and within and between networks, which will result from the adoption of sensors that conform to the WMO CIMO specifications for response time, where that can be independently certified.

3.1 | Sampling and averaging considerations

When considering air temperature outputs, it is important to consider both sensor response time and the WMO's recommendations regarding consistency of logged air temperatures, whether they are samples (single measurements) or extremes (specifically daily maximum or minimum temperatures). In cases where relatively frequent logging intervals are not required, such as the averaging of samples to obtain hourly or daily mean temperatures (only), averaging 60 s samples over the chosen period will normally suffice. For shorter (sub-hourly) intervals and for statistics such as maxima and minima, careful consideration should be given to sampling and averaging intervals. In such cases, the WMO's CIMO guide (WMO, 2023, annex 1.A) recommends a 60 s output averaging time, with sub-minute sampling frequency at intervals close to the time constant. However, this contradicts recommendations in the WMO's *Instruments and Observing Methods* report, which suggests sampling at four times per time constant (WMO, 2021, table 7.3.2). All sub-60 s samples are then averaged to derive 60 s output data points that are then taken to represent the base temperature value at that time. However, as recent work in Australia points out (Ayers & Warne, 2020; Trewin, 2022), such sample temperatures at any given moment are themselves necessarily an integral over a period of time dictated by the time constant of the sensor in use.

With this in mind, a logical approach to sampling air temperatures at short intervals (typically 1–10 min) would be to establish a sampling protocol approximately equal to the sensor's response time, taking into account the ventilation rate for the screen or shield in which the sensor resides, as suggested in the following examples:

Example 1: Consider a PRT housed within a typical Stevenson screen, with an assumed ventilation rate of $\sim 0.2\,\mathrm{m\cdot s^{-1}}$. Assume that, from laboratory tests or manufacturer's specification datasheets, we know this PRT's τ_{63} response time in air is 15 s (Table 1). Given these parameters, it would be appropriate to sample this sensor every 15 s, then average the most recent four samples to obtain a 60 s mean at every sampling time; that is, a value updated every 15 s.

Example 2: If the same sensor was instead housed in an aspirated shield, where a ventilation speed of $3\,\mathrm{m\cdot s^{-1}}$ is typical, its response time could be expected to decrease to about 8 s (Table 1). For this configuration, a sampling interval of 10 s would be more appropriate, with the most recent six samples averaged to derive 60 s values, updated every 10 s. Note, however, that reducing the sampling interval below 5 s would offer little benefit, increase computational load, and risk self-heating of the PRT sensor.

In both examples, the latest 60 s mean is itself updated at each sample iteration, 10 or 15 s later depending upon the sampling interval. Over a set period (e.g., hourly or 24 h intervals), the highest and lowest of these 60 s values would be logged separately as the period's maximum and minimum temperatures respectively. Such frequent updates are essential to capture temperature extremes accurately, particularly daily maximum and minimum temperatures, whose duration is not infrequently only a minute or two.

From the foregoing, it is evident that 60 s temperatures (and, from there, maximum and minimum temperatures) derived from sensors with τ_{63} or sampling intervals >20 s will be based upon fewer samples, providing fewer data points for each period's average. This increases the likelihood of unrepresentative outliers and may lead to underestimation of the true diurnal range in temperature depending on the rate of temperature change at the time of the extreme. For τ_{63} or sampling interval ≥30 s, only one sample will be possible in every 60 s interval.

Because, by long convention, "climatological mean daily (or monthly) temperatures" for any particular site are normally derived from the mean of daily maximum and minimum temperatures, rather than (say) the mean of 24 hourly values, it is particularly important to ensure that reported daily maximum and minimum values are both accurate and consistent within a network, or within a long period of record.

Response times ≥30 s are characteristic of PRTs with diameter ≥3 mm at typical airflow rates. It is advisable to replace such devices currently in use at a convenient early opportunity by units whose response time conforms to WMO CIMO recommendations. In doing so, it is important to bear in mind possible inhomogeneities that may result from doing so in long-period records or within-network record consistency. In such circumstances, a period of overlapping parallel measurements between both sensor types is recommended to quantify potential inhomogeneities, some aspects of which may be site specific. Nonetheless, increasing adoption and compliance to common WMO CIMO guidelines remains a desirable end goal.

3.2 | Why average over 60 s?

Although a 60 s averaging period appears at first to negate the benefit of a faster response sensor, it is supported by both theoretical and practical reasoning. Firstly, response-time theory indicates that, for a first-order response, 95% of a step change in the input value (air temperature, in this case) will be attained at or close to $3\tau_{63}$. For sensors with the guideline response time of <20 s, this means that 95% of that change will be experienced within 60 s (i.e., within the span of the next complete 60 s output data point). Secondly, 60 s averaging ensures some degree of continuity of measurement over time with traditional liquid-in-glass thermometry. Variability across these instruments (including types such as mercury-based maximum or alcohol-based minimum thermometers), along with differences in ventilation speed and instrument age, makes it difficult to determine the exact response time of any individual instrument at any moment, although some experimental results have been published (Benbow *et al.*, 2018).

4 | CONCLUSIONS

These results provide robust, replicated, and independent evidence that the 1.5 mm air temperature sensor surpasses the WMO recommended time constant of ≤20 s at typical ventilation levels within Stevenson-type thermometer screens or radiation shelters. To our knowledge, it is the first sensor intended for meteorological/climatological air temperature measurements to achieve this standard. The new PRTs tested at Logan replicated some of the work in Burt and de Podesta with similar results. This work also tested several additional PRTs tested at both facilities, further emphasizing the remarkable paucity of commercially available sensors that demonstrably conform to WMO time-constant requirements with but one, built-for-purpose exception.

Although improved sensor response time is certainly a desirable characteristic for the reasons advanced previously, caution is needed, as record inhomogeneities may arise when traditional or existing air temperature sensors are replaced with others with different characteristics, particularly those with faster response times and/or differing sampling/averaging algorithms. Without careful advance consideration to such details at site level, such inhomogeneities may develop within existing long-period air temperature records, or between stations within a network utilizing differing sensor types. Closer adherence to WMO CIMO guidelines is a desirable objective, but a careful overlap programme between “current” and “new” equipment (including combination sensors and screens/shields as appropriate) should be conducted in advance of the planned changes to gather quantitative data regarding possible inhomogeneities. Within a network such as a region or country, such overlap programmes may perhaps be most usefully and easily conducted at a handful of representative sites, rather than necessarily replicated at every measurement location.

Examples of significant changes include the replacement of traditional mercury thermometers with PRTs that have different response characteristics, the introduction of PRTs with faster response times, or the adoption of aspirated methods for measuring air temperatures, the latter offering the advantage of improved airflow and reduced response times. Aspirated methods are increasingly favoured for climate reference networks, such as the United States Climate Reference Network (Diamond *et al.*, 2013), and a “working demo” Climate Reference Site in Europe (Merlone *et al.*, 2024). However, such short-term challenges should not discourage the parallel trial and adoption of methods and instruments intended to provide demonstrably improved representation of air temperatures at local, regional, and global levels.

AUTHOR CONTRIBUTIONS

SB: Conceptualization; methodology; investigation; data curation and analysis; project administration; writing – original draft, final review and editing. DB: Conceptualization; investigation; data curation, validation and analysis; writing – final review and editing. A preliminary version of the results outlined in this article was presented by DB at the WMO TECO conference in Vienna, Austria, in September 2023. A copy of the presentation (slides and a video recording) is available at https://community.wmo.int/en/activity-areas/imop/teco-2024-presentations (accessed December 16, 2024).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

Copies of the individual PRT laboratory test results, suitably anonymized by manufacturer/supplier, are available on reasonable request from either co-author.

DISCLAIMER

None of the information provided in this work should be taken as an endorsement of any single manufacturer or product.

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REFERENCES

Ayers, G.P. & Warne, J.O. (2020) Response time of temperature measurements at automatic weather stations in Australia. *Journal of Southern Hemisphere Earth Systems Science*, 70, 160. Available from: https://doi.org/10.1071/es19032

Benbow, D., Dollery, I. & Warne, J. (2018) *Instrument test report 714: response times of surface thermometers*. Australia: Bureau of Meteorology.

Burt, S. (2022) Measurements of natural ventilation within a Stevenson screen and its influence on air temperature and humidity records. *Geoscientific Instrumentation, Methods and Data Systems (EGU)*, 11, 263–277. Available from: https://doi.org/10.5194/gi-2021-31

Burt, S. (2024) *The weather observer's handbook, second edition*. Cambridge, New York: Cambridge University Press. Available from: https://doi.org/10.1017/9781009260534

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

Diamond, H.J., Karl, T.R., Palecki, M.A., Baker, C.B., Bell, J.E., Leeper, R.D. et al. (2013) U.S. climate reference network after one decade of operations: status and assessment. *Bulletin of the American Meteorological Society*, 94(4), 485–498. Available from: https://doi.org/10.1175/bams-d-12-00170.1

Foken, T. (Ed.). (2022) *Springer handbook of atmospheric measurements*. Cham, Switzerland: Springer International Publishing, p. 1748.

Harrison, R.G. (2010) Natural ventilation effects on temperatures within Stevenson screens. *Quarterly Journal of the Royal Meteorological Society*, 136, 253–259. Available from: 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, 402–408. Available from: https://doi.org/10.1002/qj.745

Harrison, R.G. (2014) *Meteorological measurements and instrumentation*. Chichester: John Wiley & Sons. Available from: https://doi.org/10.1002/9781118745793

Harrison, R.G. & Burt, S.D. (2021) Air temperature uncertainties from naturally ventilated thermometer screen measurements. *Environmental Research Letters*, 3, 61005. Available from: 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, e1256. Available from: https://doi.org/10.1002/asl.1256

International Organization for Standardization (ISO). (2007) *ISO 17714 meteorology — air temperature measurements — test methods for comparing the performance of thermometer shields/screens and defining important characteristics*. Geneva: International Organization for Standardization (ISO).

Merlone, A., Beges, G., Bottacin, A., Brunet, M., Gilabert, A., Groselj, D. et al. (2024) Climatological reference stations: definitions and requirements. *International Journal of Climatology*, 44, 1710–1724. Available from: https://doi.org/10.1002/joc.8406

Trewin, B. (2022) A climatology of short-period temperature variations at Australian observation sites. *Journal of Southern Hemisphere Earth Systems Science*, 72(2), 117–125. Available from: https://doi.org/10.1071/es21027

World Meteorological Organization (WMO). (2021) Instruments and Observing Methods Report No. 136: Generic Automatic Weather Station (AWS) tender specifications. Available from https://library.wmo.int/records/item/57830-generic-automatic-weather-station-aws-tender-specifications (accessed 22 Nov 2024).

World Meteorological Organization (WMO). (2023) *WMO No.8 - vol I - guide to meteorological instruments and methods of observation (CIMO guide)* - 2023 edition. In: *measurement of meteorological variables: Volume I*. Geneva: WMO, p. 551 Available from WMO permalink https://library.wmo.int/idurl/4/68695 (accessed 22 Nov 2024)

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