Accuracy of daily extreme air temperatures under natural variations in thermometer screen ventilation

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RESEARCH ARTICLE

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Accuracy of daily extreme air temperatures under natural variations in thermometer screen ventilation

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Abstract

Accurate air temperatures underpin environmental research. Most professional meteorological air temperature measurements still expose thermometers within traditional, naturally ventilated screens. Their representation of true air temperature depends on screen airflow, and therefore local winds. Accuracies of daily maximum (T_{max}) and minimum (T_{min}) air temperatures are assessed by comparison between a naturally ventilated large conventional screen and a co-located aspirated reference screen. In over 1200 days' data, the naturally ventilated T_{min} and T_{max} both showed small (median $< 0.06°C$) cold bias, but, in 1% of cases, warm T_{max} bias and cold T_{min} bias $>|1°C|$. The T_{min} cold bias is associated with calm clear nights, and the T_{max} warm bias events with calm winter days at low sun angles, allowing solar heating of the screen. The prevalence of poor natural ventilation, potentially affecting T_{min} and T_{max}, is estimated across European sites. Poor ventilation occurred at T_{min} for 12% of values, and at T_{max} for 4%. Climatological averaging will reduce these effects, but, without corroborating wind data, statistical changes in T_{min} or T_{max}, including identifying "Tropical Nights" ($T_{min} > 20°C$) or occurrences of winter extremes, may have limited value. Wider adoption of aspirated thermometer screens, with an initial overlap period, will largely eliminate these effects.

KEYWORDS

air temperature, aspirated screen, climate change, meteorology, temperature error, thermometer

1 | INTRODUCTION

Accurate air temperature measurements are essential for environmental and climate research, for which a thermometer is usually operated within a shield or screen. These protect against the effects of short-wave (solar) and long-wave (terrestrial) radiation, and precipitation. Naturally ventilated thermometer screens still comprise most of these enclosures, commonly the white, double-louvred Stevenson screen first proposed in 1864 and variants thereof, such as the Cotton Region Shelter used in the United States (Middleton, 1966; Naylor, 2019; Stevenson, 1864). For representative air temperature measurements, these enclosures require sufficient windspeed at the site and time of observations to ensure adequate airflow across the thermometer. It has long been recognised that these conditions are not always fulfilled, for example on "…calm, sunny days…" (Aitken, 1884). In the absence of forced ventilation, the natural daily variation in surface wind speed, which, over land, increases during the day and decreases at night, will lead to different accuracies in daily air temperature maxima and minima (Harrison, 2010). This is because the daily minimum T_{min} typically occurs around dawn, when wind speeds (and therefore also the naturally ventilated screen airflow) tend to be at, or close to, their diurnal minimum, whereas the daily temperature maximum T_{max} tends to occur later in the day, when wind speeds are nearer their diurnal maximum.

Aspirated methods of measuring air temperature, whereby forced ventilation ensures a steady flow of external air over the temperature sensor, are increasingly recommended by the World Meteorological Organisation (WMO) as the preferred method of measuring air temperature (WMO, 2021). In such devices, a structure around the sensor houses an impeller mechanism to draw air over the sensor, which also shields the sensor from radiation and precipitation. Temperature records from aspirated devices remain rare in most countries; in the UK, for example, there are, as yet, only a few such sites, and none in the UK Met Office operational network. In the United States, the US Climate Reference Network, established in the early 2000s, comprises 114 sites in 'pristine locations', all of which use multiple aspirated temperature sensors to measure air temperature (Diamond et al., 2013).

As daily temperature maxima and minima are commonly recorded and sometimes compared statistically, the Stevenson screen measurement biases at those times are important to quantify. This question is pursued here through an extended comparison experiment, using simultaneous automatic measurements in co-located aspirated and naturally ventilated thermometer screens. The differences found between the measured extreme temperatures in the two situations are assessed against wind speed and the local radiation exchange, to identify deficiencies and examine the underlying causes.

2 | BACKGROUND

The representativity of temperature measurements made in a naturally ventilated screen has been investigated in various trials and experiments, generally following the methodology of comparison with a reference device, such as an aspirated thermometer (Painter, 1977), a thermometer of negligible radiation error (Harrison, 2010; Nakamura & Mahrt, 2005) or with a Stevenson screen having forced ventilation (Hoover & Yao, 2018). The greatest differences found were 0.8°C (Yang & Liu, 2017), 2.1°C (Hoover & Yao, 2018), and 0.54°C (Buisan et al., 2015). Comparing naturally and actively ventilated beehive-style screens at 2.4 m, the naturally ventilated thermometer temperature exceeded that of the actively ventilated thermometer by up to 2°C during the day, and was occasionally colder nocturnally during low wind speeds (De Ridder et al., 2023). Such studies demonstrate the benefit of aspirated devices, which are now increasingly used for climate reference measurements (Diamond et al., 2013). While these reported differences represent extremes of observed differences in these studies rather than normal conditions, the magnitude is similar or greater than observed climatological trends in high temperature extremes—for example, within England, where the annual maximum temperature trend is typically $<1°\mathrm{C}\cdot\mathrm{decade}^{-1}$ (Christidis et al., 2020). This should not be taken to suggest or imply that such extremes arise solely from the behaviour of screen-mounted thermometry under extreme conditions. As shown subsequently, this is demonstrably not the case, as some of the largest differences in maximum temperature between the aspirated and naturally ventilated screens occurred close to the winter solstice, rather than in extreme conditions of summer months.

Biases in air temperature measurements between naturally ventilated thermometer screens and a reference measurement, often a nearby aspirated thermometer, arise due to a combination of radiative exchange processes with their local environment, their internal thermal variations, and their enclosed thermometer's time response. Within a Stevenson screen, a complex spatial temperature distribution usually exists, as shown by fluid dynamical modelling (Yang et al., 2016), which varies with screen or shelter size, implying a size or volume effect (Buisan et al., 2015), solar angle and intensity, wind speed and direction, and screen surface conditions including albedo and surface wetness. The radiation environment encountered by a thermometer will therefore not be uniform, especially in low ventilation conditions (Bell et al., 2022). Additional complicating aspects arise if the screen is coated with liquid water, ice or snow, for example from condensation and precipitation, but it is the major effect resulting from variable ventilation which is considered here.

In a comparison between naturally ventilated and aspirated screen temperatures at Reading University Atmospheric Observatory (RUAO), 50% of temperature differences between the two different screens were within ±0.07°C, with only 2% beyond about ±0.5°C (Harrison & Burt, 2021). Despite the mostly negligible temperature bias, some of the larger differences occurred in the daily temperature extremes of maximum and minimum (T_{max} and T_{min}) which are important quantities conventionally recorded in meteorology. For RUAO the median wind speed at T_{min} is 0.8 m·s^{-1} compared with 2.4 m·s^{-1} at T_{max}, using 1997–2022 wind data determined at 2 m above the surface.

Additionally, air speeds within a screen are only a fraction of those outside it. For a standard Stevenson screen, the measured ventilation speed within it is only 7% of the outside wind speed at the standard measurement height of 10 m (or 10% of the 2 m wind speed) (Burt, 2022), and is likely to be even less for a larger screen. A further effect of poor ventilation is to lengthen the response time of the temperature sensors (Burt & de Podesta, 2020), which, in calm conditions, can exceed 20 min for a Stevenson screen (Bryant, 1968; Harrison, 2010). The combined effects of heterogeneous radiation environments and sensor time response can produce temperature uncertainties of ±0.5°C or more when wind speeds at screen height (2 m) are light, typically 0.5 m·s^{-1} or less (Harrison & Burt, 2021). These local aspects, which feed through into the diurnal temperature range (DTR) are increasingly considered in applying corrections to climate records (Thorne et al., 2016).

3 | METHODOLOGY

For this comparison of effects on T_{max} and T_{min}, records made between 7 November 2019 and 28 February 2023 at Reading University Atmospheric Observatory (RUAO) were used (Harrison & Burt, 2023), using the same methodology described by Harrison and Burt (2021). Two identical calibrated platinum resistance thermometers (PRTs, see, e.g., Foken & Bange, 2021) were sampled and logged every 1 s. One PRT was mounted in a RM Young model 43502 radiation shield (330 mm high × 200 mm diameter), aspirated by an electric fan, yielding a reference temperature T_{asp}. The other PRT was in a MetSpec "large" Stevenson screen (internal dimensions 1145 × 420 × 430 mm), yielding T_{scrn}. The screens were arranged alongside each other at RUAO. (An image of the arrangement is provided in Figure S1). The Young aspirated screen was chosen as it has been used successfully in similar comparisons undertaken by other bodies, including the WMO (Lacombe et al., 2011), together with a continuing decade-long intercomparison at a nearby site by one of the authors (Burt, 2012). Both PRTs had excitation currents of 50 μA, to minimise their self-heating (Harrison & Rogers, 2006). Other meteorological measurements made simultaneously at RUAO include solar radiation (direct beam S_b, and on a horizontal surface S_g), net radiation (R_n) and the wind speed at various heights, including at 2 m above the surface (u_2).

The WMO convention for determining the daily maximum or minimum temperature from automatic records is to average over a 60 s period centred on the extreme value (WMO, 2021). For data processing convenience, this work instead derived equally spaced 1 min average temperatures from the 1 s samples, from which the greatest and least values between 0 UTC to 24 UTC were selected as T_{max} and T_{min}. This methodology leads to small differences (±1 min) in timing, but with negligible (<0.1°C) change in the extreme value obtained.

4 | RESULTS

Figure 1 shows histograms of the differences between the 1 min values from the two thermometers, expressed as the bias of the naturally ventilated screen temperature against the reference (i.e., $T_{scrn} - T_{asp}$). Figure 1a shows all 1 min temperature differences obtained during the comparison (~1.7 million samples). The characteristics of this distribution are summarised in Table 1: the median difference is 0.01°C, with 50% of the differences lying between −0.05 and 0.12°C. Because the daily maximum and minimum values are important for summarising a day's temperature variation, only these extreme values are considered further here. Figure 1b,c shows the distributions of screen biases at the daily minima and maxima respectively from the 1 min values. (This information is also provided against temperature in Figure S2.) Both histograms of the extremes have a small median bias which is negative, −0.02°C for minima and −0.06°C for the maxima.

Table 1 summarises the subset of values occurring at the daily (i.e., 0000 UTC to 2359 UTC) temperature maximum and minimum (1210 data points): the biases in the minima or maxima exceed ±1°C in only 1% of cases. Highlighting low wind speeds ($u_2 < 0.5$ m·s^{-1}) in Figure 1b,c shows that u_2 is generally smaller for temperature minima than maxima, with cases of lower ventilation apparent in some of the temperature extremes. It should be noted that the values in Table 1 represent the statistics of individual events, which may not affect the climatological annual and monthly mean temperatures derived from them. This depends on the occurrence and distribution of the events, on which there are other influences, such as the persistence of different weather conditions.

To investigate whether there is a systematic behaviour, the same data have been organised differently, with the Stevenson screen temperature biases plotted against time of year in Figure 2, for daily temperature minima (a) and maxima (b). For the minima (Figure 2a), the cold biases occur throughout the year at low wind speeds. In contrast, for the temperature maxima (Figure 2b), many of the warmer biases are clustered in the late autumn and winter (November to February). A characteristic of

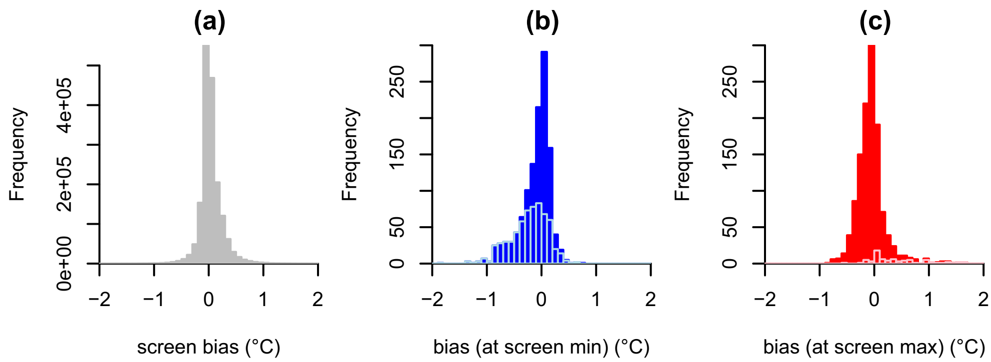

FIGURE 1 Distribution of Stevenson screen temperature biases against a co-located aspirated screen thermometer for (a) all times of day, (b) Stevenson screen temperature daily minima and (c) Stevenson screen temperature daily maxima. In (b) and (c), sub-histograms of values having simultaneous 2 m wind speeds (u_2) less than 0.5 m·s^{-1} are identified with a light-coloured outline.

TABLE 1 Summary statistics of temperature differences between aspirated and Stevenson screens.

Quantity	Sample count	Lowest percentile (°C)	Lower quartile (°C)	Median (°C)	Mean (°C)	Third quartile (°C)	Upper percentile (°C)
All 1 min values ($T_{scrn} - T_{asp}$)	1,737,418	−0.50	−0.05	0.01	−0.04	0.12	0.72
($T_{scrn} - T_{asp}$) at Stevenson screen daily minima	1210	−1.01	−0.23	−0.02	−0.11	0.07	0.38
($T_{scrn} - T_{asp}$) at Stevenson screen daily maxima	1210	−0.62	−0.20	−0.06	−0.04	0.03	1.18

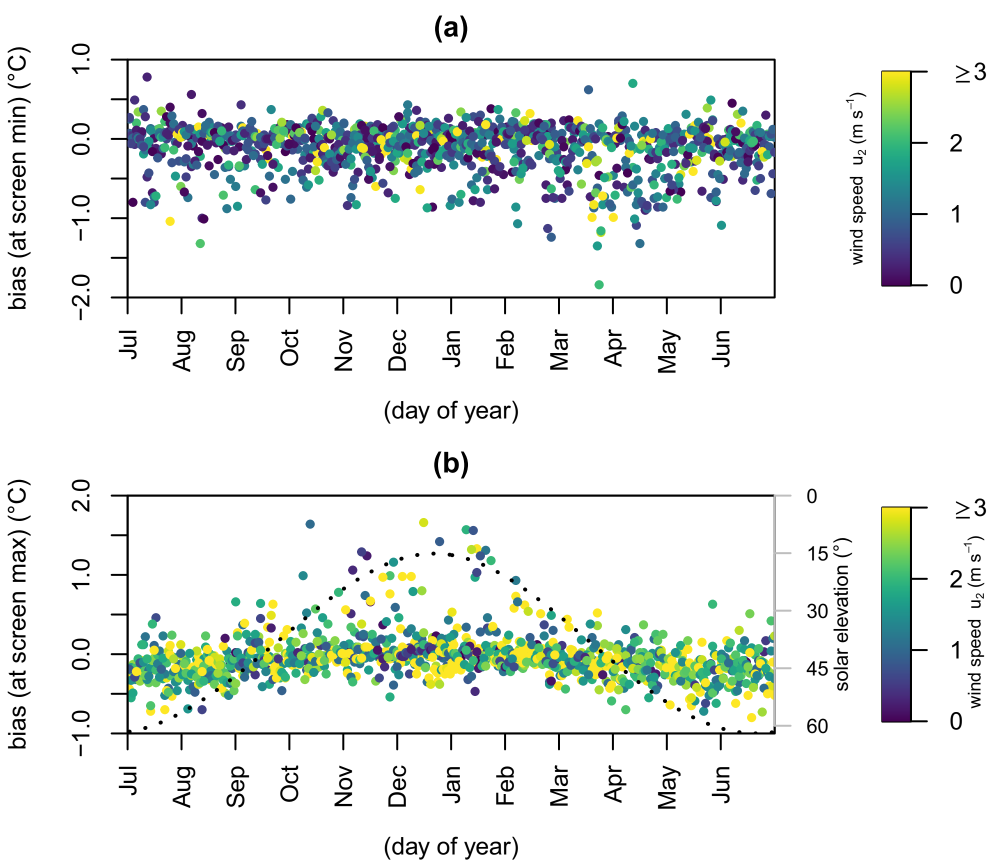

FIGURE 2 Bias of naturally ventilated Stevenson screen air temperatures (7 November 2019 to 28 February 2023), for (a) daily temperature minima and (b) maxima, using 1 min averages. In (b), the calculated solar elevation angle at noon is also plotted (dashed grey line—note reversed axis scale). (Colour scales show the 2 m wind speeds u_2 at the minima and maxima times; *x*-axis ticks mark the beginning of each month.)

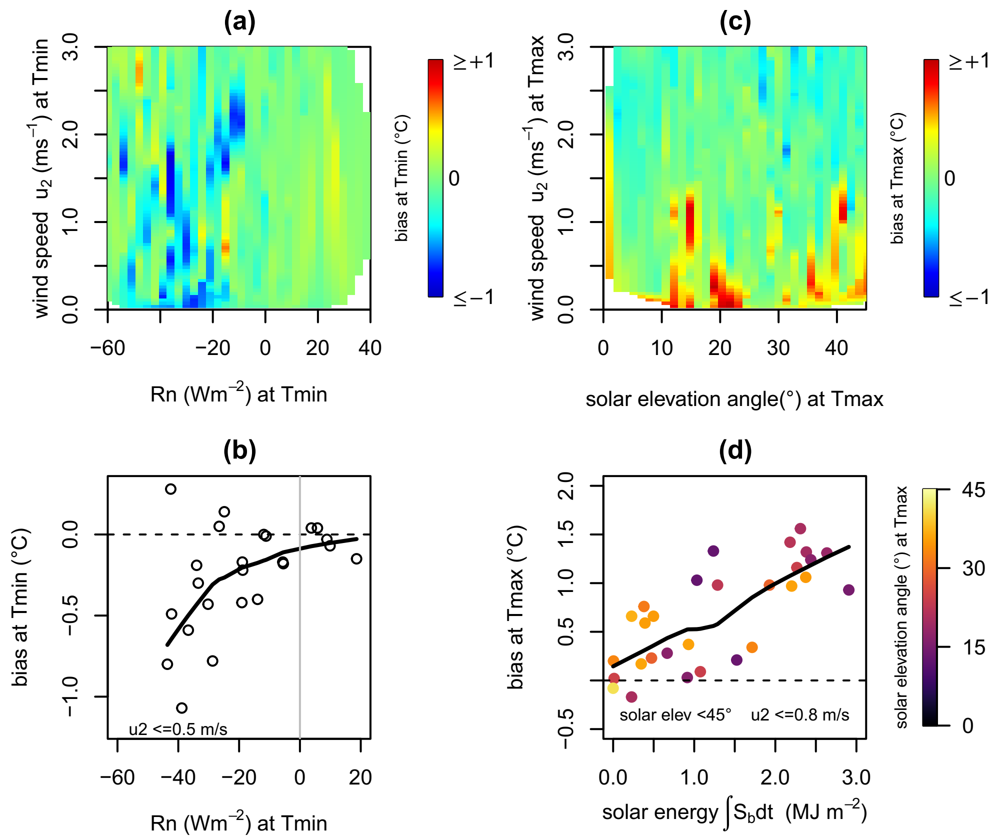

FIGURE 3 Stevenson screen temperature biases for (a) T_{min} and (c) T_{max}, plotted against net radiation R_n and 2 m wind speed (u_2) for T_{max}, and against solar elevation angle and u_2 for T_{max}, (b) shows low ventilation T_{min} temperature bias against R_n. Panel (d) shows low ventilation T_{max} temperature bias (with points coloured by solar elevation at the same time) plotted against the integrated direct solar beam S_b during the 60 min preceding T_{max}. Lowess fitting lines determined by software have been added to (b) and (d).

winter is low solar elevation angle, and this variation is overplotted in Figure 2b, calculated using the accurate method of Yallop (1992). This suggests that many of the greatest T_{max} warm biases are associated with solar elevation angles of less than 30°. Figures S3 and S4 show example days having large bias at T_{min} and T_{max} respectively. For the T_{max} case (Figure S4, 15 January 2021), only intermittent sunshine at low solar elevation was needed to generate a warm bias, when the wind speed was near zero. For the T_{min} case (Figure S3i, 17 April 2021), nocturnal clear skies led to nocturnal cooling. Further, Figure S3ii demonstrates a day (14 August 2022) when the relative humidity was well below saturation at T_{min}, emphasising that the effect is not due to condensation, but dominated by the reduced ventilation at that time.

A more detailed comparison of the biases in the minima and maxima is given in Figure 3. Figure 3a shows the cold bias at T_{min} plotted against the simultaneous u_2 and net radiation, R_n, which is the difference between downwelling radiation and upwelling radiation. (This measurement combines the solar "short wave" and terrestrial "long wave" contributions, considered positive when downwelling radiation dominates). From Figure 3a it is evident that the cold biases mostly occur at night ($R_n < 0$), tending to be associated with smaller u_2 values. To verify that the cold bias is associated with radiation environment rather than air temperature, the bias in the low ventilation cases (for which $u_2 < 0.8$ m·s^{-1} is used as wind speeds are greater around T_{max}), is compared against R_n (Figure 3b), with a calculated lowess line added (Cleveland, 1981) to highlight the trend present. This demonstrates that the cold bias at T_{min} increases as the upwards radiative loss also increases. While the sensor response time is clearly relevant in both screen types, the greater airflow within the aspirated unit (typically 3–6 m·s^{-1} in the unit used in this experiment) will make the response of the aspirated sensor more rapid, compared with that of the larger naturally ventilated screen (Burt & de Podesta, 2020). However, if the observed temperature bias were due primarily to sensor inertia (i.e. from an increased response time due to poor ventilation), the minimum temperature within the naturally ventilated screen would tend to be somewhat greater than that within the aspirated screen, not less, as observed.

Figure 3c provides a similar comparison but for T_{max}, against u_2 and solar elevation angle. The warm biases occur for smaller u_2, and especially at solar elevation angles less than 25°, that is, mostly during December and January. To establish whether this results from a direct radiative effect on the screen, the screen bias was compared with the incoming solar beam (S_b), measured by a solar tracking pyrheliometer. Better agreement was found between the screen bias at T_{max} and the integrated S_b throughout the previous 60 min, than with the instantaneous S_b (see also Figure S5), and the bias at T_{max} during poor ventilation is plotted against the integrated S_b in Figure 3d. This shows that the bias in these conditions results from sustained solar heating of the naturally ventilated screen, at least in the hour before the maximum temperature was reached. As for the minimum temperature, if the bias at maximum temperature were due primarily to longer sensor time response in poor ventilation conditions, rather than heating of the screen structure by solar radiation as is proposed, the maximum temperature within the naturally ventilated screen would be reduced compared with that within the aspirated screen, not greater, as observed.

5 | DISCUSSION

For a poorly ventilated traditional thermometer screen in light winds or calm conditions, these results show a cold bias in some daily minimum temperatures and a warm bias in some daily maximum temperatures. In such light wind conditions, the time response of the naturally ventilated screen thermometer is relatively slow, hence the temperature biases are more strongly associated with changes in the exchange of solar and terrestrial radiation from the thermometer screen, rather than air temperature variations. For the affected daily maxima, this occurs due to direct solar (short wave) heating (see Figure S6), but for the daily minima affected the radiation exchange occurs through nocturnal terrestrial (long wave) radiation cooling (see Figure S7). Effects on the daily maxima are greatest during winter, due to the combined effect of low elevation solar radiation and poor ventilation. Hence, whenever the surface ventilation is poor, the daily maximum or minimum temperatures recorded in the naturally ventilated screen will not be solely related to local air temperature, and indeed may differ from it considerably.

The importance and prevalence of these effects on the daily extremes will vary from site to site, as they depend on the local daily wind speed variations. Whilst the detailed results presented are specific to the RAUO site, similar physical effects on naturally ventilated thermometer screens have been observed in a decade-long investigation by one of us (SDB) at another southern UK site, indicating that they are not site-specific. Without widespread similar arrangements to evaluate this fully, one way of constraining how commonly temperature minima and maxima might be affected is through considering how frequently poor ventilation conditions occur at multiple sites. The HadISD database (Dunn, 2019; Dunn et al., 2012, 2014, 2016; Smith et al., 2011) is suitable for this, as it provides sub-daily information from very many observing sites. Northern hemisphere sites providing wind data in the European region have been extracted from HadISD, and the locations of the 2337 sites considered are shown in Figure 4.

In general, the times of daily temperature minima and maxima will vary at individual sites, and with weather conditions. To evaluate the prevalence of poor ventilation, the T_{min} time was assumed to occur at 06 UTC and T_{max} at 15 UTC, although this is an approximation—the actual daily minimum and maximum times of day will diverge from this at sites located across Europe in different situations and in different weather conditions. The wind speed measurements in HadISD are reported for 10 m, that is, u_{10} rather than u_2 which is more characteristic of thermometer height conditions. For low wind, that is, "poor ventilation" estimation purposes, a threshold u_2 of 0.5 m·s^{-1} as a criterion for poor ventilation was assumed, following the finding of Harrison and Burt (2021) that $u_2 = 0.5$ m·s^{-1} was required to limit the naturally ventilated screen's bias to ±0.5°C. An equivalent threshold on u_{10} was found from $u_{10} = 1.28\ u_2$. Wind speeds were accordingly extracted from HadISD for 06 UTC and 15 UTC, and the proportion of cases with wind speeds below the u_{10} threshold derived, for each site (Figure 4a,b). As for the RUAO site, it is very evident from Figure 4a,b that the "poor ventilation" criterion is more commonly met at "T_{min}" (06 UTC) compared with "T_{max}" (15 UTC). Central and eastern European regions, where there are many sites, show this effect more strongly than in the southern UK.

Table 2 provides summary statistics. This shows that poor ventilation conditions for "T_{min}", as defined here, occur at the sites in a median 11.9% of values, and, at "T_{max}", in 3.9% of values. If the 15 UTC wind selection is restricted to winter (December–January–February) when the low solar elevations leading to large biases occur, 6.1% of T_{max} values would be affected on average (see also Figure 4c). In some cases, a daily extreme value associated with low ventilation might also become the month's extreme value.

6 | CONCLUSIONS

Low wind speeds strongly influence the accuracy of daily temperature maxima and minima observed using naturally ventilated thermometer screens. This in no way challenges the important finding that the global climate overall is warming, which is found from averaging across very many sites, greatly reducing the site-specific uncertainties of different kinds. However, if maximum or

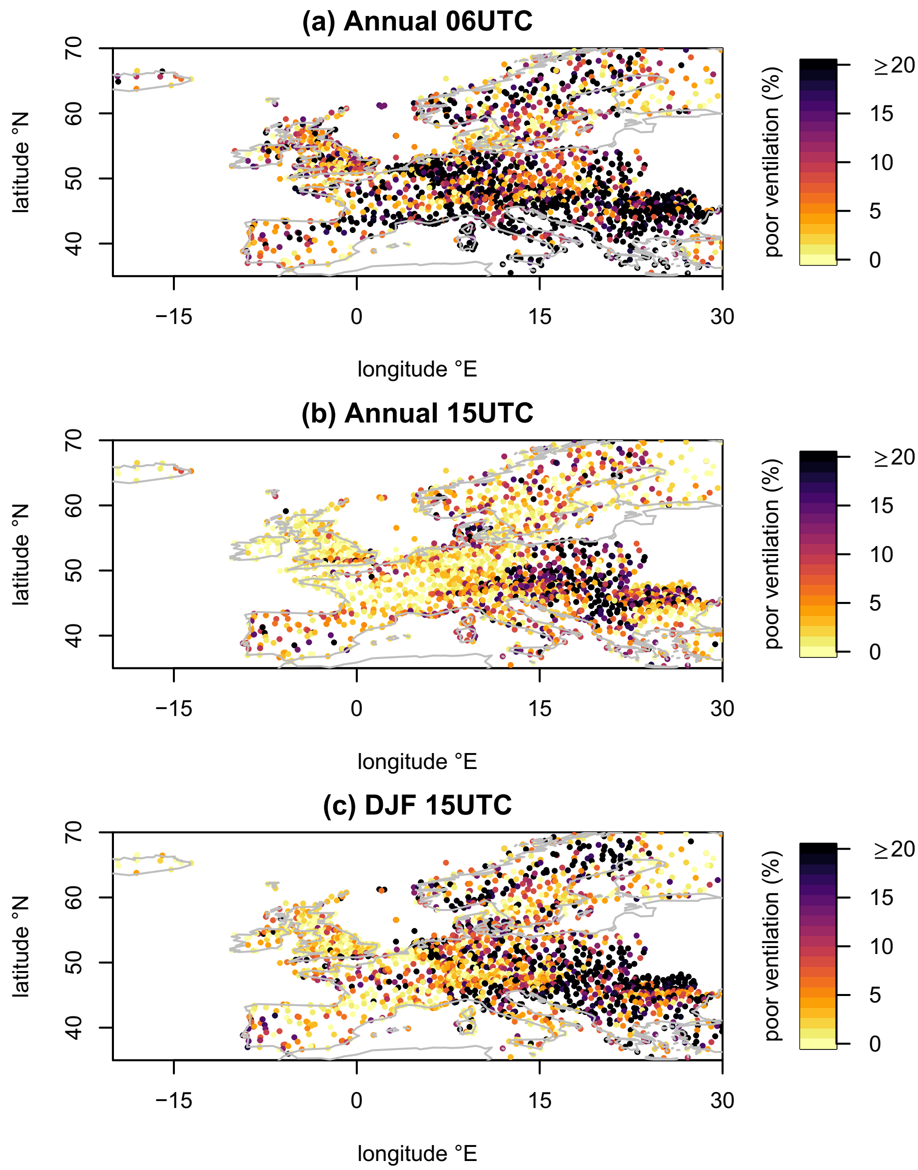

FIGURE 4 Sites in the European region, coloured by proportion of weather reports of poor ventilation conditions (defined as $u_2 < 0.5\ \mathrm{m \cdot s^{-1}}$) at (a) 06 UTC annually, (b) 15 UTC annually and (c) 15 UTC during winter (December–January–February, DJF).

TABLE 2 Summary of poor ventilation ($u_2 < 0.5\ \mathrm{m \cdot s^{-1}}$) cases.

Circumstances	Number of observations across all sites	Number of poor ventilation cases (all sites)	Median percentage of poor ventilation cases (all sites)
06 UTC	29,103,323	5,115,891	11.9
15 UTC	27,771,587	1,872,656	3.9
15 UTC (DJF)	6,912,144	740,301	6.1

minimum temperatures are used from a single site or compared between sites, the limitations identified may influence the findings. Awareness is therefore needed in statistical use of the daily extremes, especially if they occur when the bias is expected to be large, or if the analysis depends on exceedances beyond a threshold. For example, a "Tropical Night" is defined as requiring $T_{\mathrm{min}} > 20°\mathrm{C}$. Generally, T_{min} occurs during light or calm winds when naturally ventilated screen thermometers are least effective in representing air temperature. Such circumstances of poor ventilation seem likely to persist on the very warmest nights, as, whilst hardly any Tropical Nights have yet occurred at Reading, the next warmest nights in the 25 year RUAO record ($T_{\mathrm{min}} > 18°\mathrm{C}$) have a median wind speed at T_{min} which is statistically indistinguishable from all other nights (Figure S8).

Similarly, winter temperature maxima, the changes in which and the implied warming rates are of general interest (BBC, 2022), could arise—or be exaggerated—from direct solar heating of a Stevenson screen at low solar elevations even with broken cloud, rather than from an actual extreme value of air temperature as usually assumed. In principle this could occur at many locations, as 73% of the global weather-reporting sites (6950 of 9553 in HadISD) are situated between latitudes 30° N and 60° N, where solar elevation angles below 45° occur in winter (Figure S9).

This experimental comparison indicates that corroborating wind speed information will always be necessary to assess whether naturally ventilated thermometer measurements are fully representative of air temperature at the daily maximum or minimum. This could either utilise additional measurements at the same site or, possibly, meteorological reanalysis data. In general, however, the variability inherent in natural ventilation at a specific site could be entirely removed if aspirated thermometer screens became more widely used, allowing more accurate evaluation of climate change whether at individual sites or across regional or country networks. Of course, any sudden change of measurement method is undesirable, but introducing aspirated measurements in parallel with conventional (Stevenson screen) records over 1–2 years as recommended by the WMO will provide both site-specific comparisons and a baseline for future climate change assessments.

AUTHOR CONTRIBUTIONS

R. Giles Harrison: Conceptualization; data curation; investigation; methodology; software; writing – original draft. **Stephen D. Burt:** Conceptualization; investigation; methodology; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data analysed is provided in the University of Reading data repository (Harrison & Burt, 2023). Further associated RUAO data is available in Miller and Harrison (2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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