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Shall I compare thee to a summer's day? Art thou more temperate?… Sometimes too hot the eye of heaven shines…

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Shall I compare thee to a summer's day? Art thou more temperate?... Sometimes too hot the eye of heaven shines *

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(* With apologies to William Shakespeare's Sonnet 18 …)

How can we compare the temperature of one summer's day to another, and how much can we trust the measurements of record air temperatures such as those of July 2019? The basics of air temperature measurement are simple enough – put a thermometer in the shade and keep air moving past it. However, the flurry around summer temperature records suggests that the details of how to do this aren't so widely appreciated. For example, how many times have you heard a radio phone-in programme asking listeners for car or garden temperature readings to compare, or a tennis commentator mentioning the temperature on centre court at Wimbledon? For a thermometer anywhere in direct sunlight, sheltered from the wind, its temperature is just that of a hot thing in the Sun. It's highly unlikely to be a reliable air temperature. Only by using well calibrated sensors with standardised exposures can we expect measured temperatures to be both representative and consistent, spatially and temporally.

Meteorologists have worked on this problem for a long time. The first liquid-in-glass thermometers appeared in Renaissance Italy in the 1640s, gradually becoming more reliable and consistent during the eighteenth century. Temperature measurements slowly became more widespread in Europe as thermometers improved, and became particularly well organised internationally in the eighteenth and nineteenth centuries. Some of the earliest reliable air temperature measurements began in national observatories making astronomical or geophysical measurements for which the temperature was merely needed as a correction factor, and many of these early "temperature series" still continue – at Oxford, for example, where records have been kept since the 1760s (Burt and Burt, 2019). The needs of modern climate science have made understanding these early meteorological technologies, and the exposure of the instruments, much more important.

To provide protection from direct sunlight, long-wave (terrestrial) radiation and other demanding environmental factors such as rain, while retaining natural airflow, thermometers are usually placed within a semi-porous shelter or shield, often referred to as a thermometer screen. Screens are almost always made from white material (externally at least) to reflect sunlight: many different designs are in use internationally. At a meteorological site they should be exposed in an open position, well away from trees and buildings, positioned for good airflow and arranged so that the hinged door to read the thermometer opens on the shady side. In the widely adopted thermometer screen originally designed by the lighthouse engineer Thomas Stevenson (1818-1887, and father of Robert Louis Stevenson), double-louvred slats are used to form the sides of the screen, to maximise thermal contact with the air passing through. Smaller cylindrical "beehive" screens based on the same principle containing smaller electronic sensors are now also widely used (Figure 1).

Figure 1. Thermometer screens. (*Left*) Stevenson-type screen at the Reading University Atmospheric Observatory. (*Right*) Beehive screen at the meteorological site of the Universitat de les Illes Balears, Palma (photographs by Giles Harrison). Both sites also have nearby wind measurements.

The actual value of the air temperature recorded within a thermometer screen depends on four main factors: the siting and exposure of the screen, how closely the in-screen temperature follows the air temperature, how quickly the sensor responds to changes in temperature, and of course the accuracy of the sensor used. A meteorological thermometer is typically a liquid-in-glass device (historically, a mercury thermometer), or increasingly an electronic sensor such as a platinum resistance thermometer. With less mass, electronic sensors can respond more quickly than traditional thermometry, so the World Meteorological Organisation (WMO) sets out observing guidelines on sensor response time, mandating that temperature measurements be averaged over 60 seconds. This helps ensure comparability of record between different instrument types (and thus historical records) and avoid spurious very short-duration maximum and minimum temperatures. Thermometers (whether liquid-in-glass or electronic) are calibrated by comparison against reference devices traceable to national and international standards, and any corrections to be applied derived.

With regular calibration checks to eliminate effects of drift, and many other precautions, consistent and representative measurements accurate to 0.1 °C become possible.

The question of how closely the screen temperature represents 'true' air temperature is much more difficult, as to assess it completely the true air temperature itself at the same place and time would be needed from a perfect - and therefore only hypothetical - method. Comparison against a reference temperature obtained by a method other than from a screen is all that can be done, and the precision experiments necessary are difficult to maintain for anything other than short periods. Numerous comparisons (or "trials") typically undertaken by national meteorological services between one design of screen and another have been published (see, for example, Meulen and Brandsma 2008, Lacombe et al 2011, Buisan et al 2015). These of course only show how to account for changes in screen design, for the more fundamental question of how well air temperature itself is measured is much less easy to determine. Nevertheless, from the few investigations available, the World Meteorological Organization (WMO) states (WMO, 2014) that worst-case temperature differences between naturally ventilated thermometer screens and artificially ventilated (aspirated) sensors and air temperature lie between +2.5 °C and -0.5 °C. With air temperatures commonly reported to ± 0.1 °C, this seems astonishingly large! However, in a year-long study at Reading University Atmospheric Observatory using a naturally ventilated screen with a careful procedure to overcome inevitable breakages of the fine wire PRTs used (Harrison, 2010), differences as large as this were indeed occasionally observed, skewed to the same slightly warm bias of the screen indicated by WMO (Figure 2). These large differences were exceptional though, as 90% of the temperature differences were well within ± 0.5 °C. Figure 2 shows that the key aspect in reducing the uncertainties is the wind flow around and through the screen, because the largest temperature differences occur in light wind or calm conditions, both by day and by night. In Figure 2b the width of the distribution can be seen to broaden at the lower wind speeds: the interquartile range of the temperature differences is 0.51 degC for 2 m wind speeds u_2 <0.5 m s^{-1} decreasing to 0.25 degC for u_2 >3 m s^{-1}. This critical dependence on screen ventilation was originally recognised by the Scottish physicist John Aitken (1839-1919, and more famous perhaps for his pioneering work on aerosols), who argued for forced ventilation through a thermometer screen (Aitken, 1884). Continuously aspirated temperature measurements have hardly ever been implemented until recently, but improved technologies mean they are increasingly regarded as reference climate measurements, in the United States (Diamond et al, 2013) and other countries, although, as yet, very few UK Met Office observing sites are equipped with aspirated sensors.

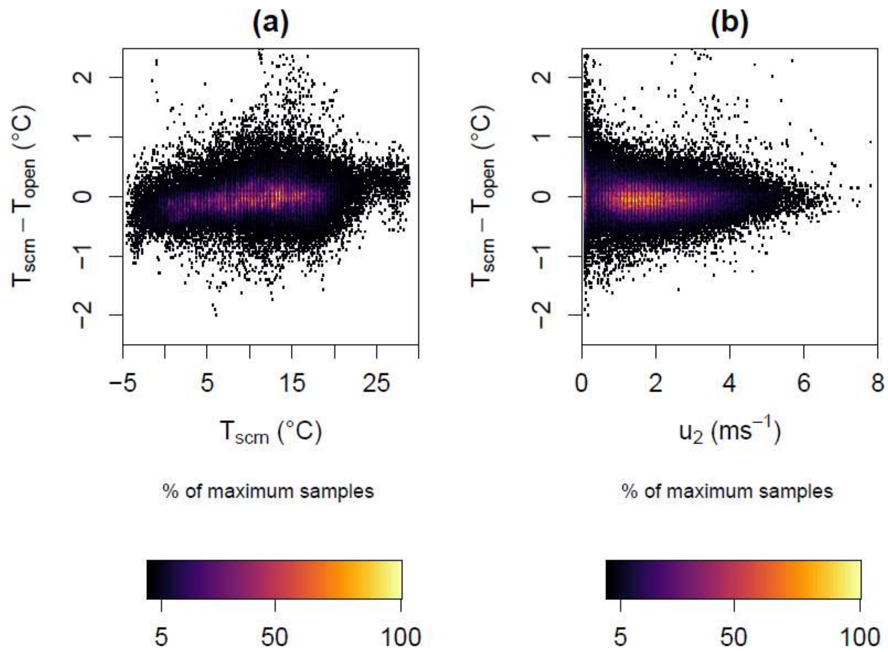

Figure 2. Difference in temperatures between a shaded fine wire platinum resistance thermometer (PRT) in open air (T_{open}) and a PRT in an adjacent screen (T_{scrn}) at the Reading University Atmospheric Observatory, plotted against (left) screen temperature and (right) the wind speed at 2m (u_2), which is approximately at screen height. The values are 5 minute averages from 1 second samples, with their distribution shown by the colour bar. (Modified from Harrison (2010)).

Ventilation is essential for rapid thermal exchange between the air, the thermometer screen and the enclosed temperature sensor itself, to try to ensure and maintain thermal equilibrium even as the air temperature fluctuates continuously. At low wind speeds, this is much less effective and the time taken for the thermometer screen to "catch up" with external air temperature changes can be quite long, as much as half an hour (Bryant, 1968). Further work at Reading Observatory showed that this improved to a couple of minutes for near-screen wind speeds of 2 ms^{-1} or greater, but that for wind speeds less than this, the lag time became considerably longer (Harrison, 2011). Because winds are often light or even calm at night, this effect is more likely to affect a night-time minimum temperature than a day-time maximum. Some maxima or minima may therefore still be under-recorded in a poorly ventilated screen, in a sheltered observing site or in light wind conditions. Lag effects in combination with the known warm bias to screen temperatures during sunshine and light winds may also result in artificially high screen temperatures, occasionally by 2 degC or more, when compared with aspirated sensors. For temperature measurements made in naturally ventilated screens, the response time of the screen is longer than that of the sensor – sometimes many times so in light winds: for aspirated temperature measurements, in contrast, the sensor response time alone is the determining factor.

Looking at the measurements made at the well-instrumented Reading Observatory for Thursday 25 July 2019 (Figure 3, right panel), the 2 m wind speed u_2 is well correlated with the screen temperature. For the times when T_{screen} was greater than 35 °C, the median u_2 was 2.3 ms^{-1}: in contrast, when T_{screen} was less than 20 °C, the median u_2 was 0.3 ms^{-1}. This shows that, although the daytime maximum was recorded under well ventilated conditions, this was not true of the nocturnal temperature minimum, which will have been less reliably determined.

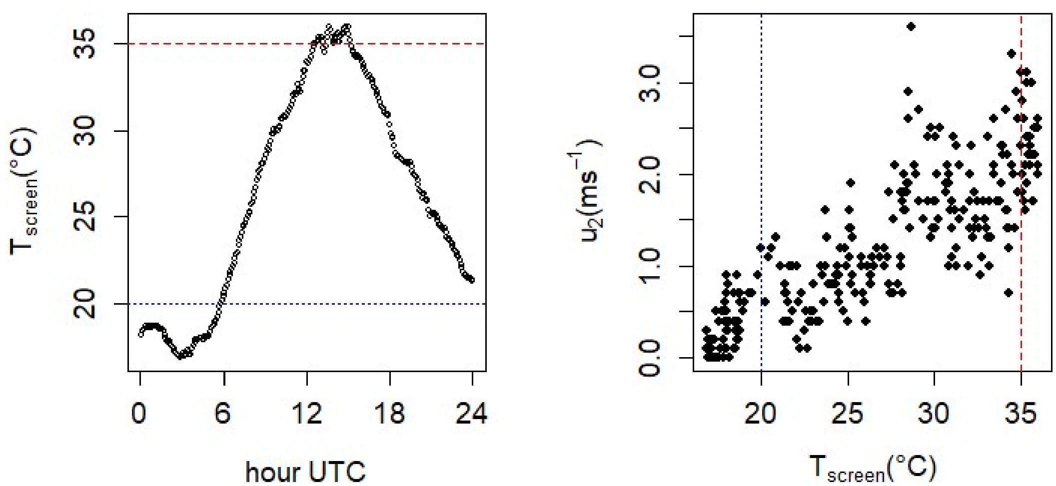

Figure 3. (Left) screen temperature at Reading Observatory on 25 July 2019, and (right) screen temperature plotted against wind speed at 2 m, using 5 min average values. The dashed red line marks T_{screen}= 35° C, and the dotted blue line T_{screen}= 20 °C. The minimum and maximum screen temperatures recorded by liquid-in-glass thermometers on this date were 16.2 °C and 36.0 °C, respectively.

The actual moment of temperature maximum is a very local phenomenon, amongst other things depending on airflow over the site, positions of heat sources and soil characteristics, urban heat island effects and, most commonly, the presence of cloud. For example, on 10 August 2003, when Reading recorded its hottest day to date at 36.4 °C, cloud materialised at Reading just before the time of the maximum in air temperature, and probably prevented a greater temperature being reached (Black et al, 2004). Even for the Reading Observatory thermometer screen on 25 July 2019, which was moderately well ventilated, temperature fluctuations lasting a few minutes, as might well have been generated beneath the broken clouds which were present, would be damped out.

The variations in maximum temperatures across nearby sites probably experiencing similar conditions on 25 July 2019 are interesting to compare (Table 1). Differences in radiative environment between extensive tarmac (Heathrow) and bleached grass surfaces (Kew Gardens) are perhaps not as great as might be expected, as both had identical maximum temperatures. On the other hand, the more open instrument enclosure at Teddington (NPL) probably contributed to a slightly lower maximum temperature there than at other London sites. Of course, results such as these can only be reliably compared as they come from locations with standard sensors, screens and exposures. The majority of such sites in the United Kingdom falls within the Met Office observing network, although there are a significant number of 'amateur' sites, and those run by other authorities, which meet or exceed the same instrumental and exposure criteria.

Table 1. Maximum temperatures reported in central and west London on 25 July 2019.

Heathrow	37.9 °C	
Northolt	37.6 °C	
Kew Gardens	37.9 °C	
St James's Park	37.0 °C	
Teddington	36.7 °C	
Reading	36.3 °C	(AWS value: maximum thermometer in screen 36.0 °C)

Excluding Reading (some 45 km west of Heathrow), the median of these sites' temperatures is 37.6 °C, with an inter-quartile range of 0.9 degC, so there is no doubt that temperatures were consistently that of an extremely hot UK summer day. Local factors can be hugely important in determining which site "wins" the maximum temperature accolade, although it is important to be scrupulous about every detail of such measurements before they are accepted (see Merlone et al 2019 for an excellent recent example from the WMO Climate Extremes committee). A new record UK screen temperature of 38.7 °C occurred at the long-running climatological site at the Botanical Gardens in Cambridge on 25 July 2019. From the arguments above, whether the air temperature there was indeed greater than that at Faversham in August 2003 (where a screen maximum of 38.5 °C was reported, from a decidedly unsatisfactory exposure – see Burt and Eden, 2004), is rather difficult to say – neither site provided simultaneous wind data at screen height, for example.

An extreme "record" screen temperature value at any one site may consequently be of only limited quantitative usefulness for comparisons, given local variability and inherent limitations in the measurement, although of course nothing here regarding the details of local measurements changes the robust result that globally, the near-surface air temperature is rising. The national maximum temperature continues to be of remarkably widespread interest, even if it isn't well appreciated how it arises, how reliably it can be measured and whether – if only the newspaper headline writers knew it – that platinum could well be the thermometric material which yields it rather than mercury.

Giles Harrison
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