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Impact of two different sized Stevenson screens on air temperature measurements

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ABSTRACT: In this study we evaluated the impact of the size of two naturally ventilated wooden Stevenson screens on air temperature measurements in the first-order meteorological station of Calamocha (northeastern Iberian Peninsula, Spain). The 1-year field experiment consisted of comparing air temperatures measured at the two most commonly sized Stevenson screens used by the Spanish Meteorological State Agency (AEMET) since last century; the medium-sized Stevenson screen employed at the second-order weather stations, versus the large-sized Stevenson screen mainly used at the first-order meteorological stations. The main objective was to report the air temperature difference between these two differently sized Stevenson screens, and to study the impact on the observed differences of some weather elements (i.e. relative humidity, wind speed, total cloud cover, atmospheric pressure and global solar radiation). The results show that the medium-sized Stevenson screen tended to overheat daily maximum air temperatures (0.54 °C on yearly average) and also air temperatures recorded at 1300 UTC. The differences on daily minimum air temperatures were negligible (−0.11 °C on yearly average). This overheating bias (not statistically significant) occurred under anticyclonic situations that lead to clear skies, high solar radiation, weak winds and low relative humidity. The bias appeared throughout the whole year but in particular during the warm season from May through October. Air temperature observations from the nearby station Daroca confirmed an overheating bias introduced by a change from a large-sized Stevenson screen to a medium-sized one in Calamocha.

KEY WORDS air temperature; two-sized Stevenson screens; intercomparison field experiment; climate series

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1. Introduction

The World Meteorological Organization (WMO, 2008) defined the optimal conditions of protection of instruments (i.e. against direct and reflected solar radiation, nights time irradiation and hydrometeors) to accurately measure air temperature. However, a standard thermometer screen has not been proposed (Van der Meulen and Brandsma, 2008) and therefore National Weather Services have been using different types of radiation shields (Parker, 1995); i.e. north-wall expositions, zinc cylinders, open screens, naturally ventilated screens, etc. (Brunet et al., 2006). This has introduced discontinuities or ‘breaks’ in long time series of air temperature (Mitchell, 1953; Jones et al., 1986; Richardson and Brock, 1995; Brunet et al., 2004), and consequently differences in the measurement of air temperature between National Weather Services all around the world.

The worldwide interest on this subject is revealed by the numerous field intercomparisons of radiation shields which have appeared in the scientific literature since the 19th century (e.g. Wild, 1879; Marriott, 1879; Gill, 1882; Whipple, 1883; Mawley, 1897; Hazen, 1885; Margary, 1924; Drummond, 1943; Chandler, 1964; Sparks, 1972; Laing, 1977; Andersson and Mattisson, 1991; Richards et al., 1992; Parker, 1994; Nicholls et al., 1996; Nordli et al., 1997; Böhm et al., 2001; Van der Meulen, 2003; Brunetti et al., 2006; Perry et al., 2007; Van der Meulen and Brandsma, 2008; Brandsma and Van der Meulen, 2008; Azorín-Molina and Azorín-Molina, 2008; Martínez-Ibarra et al., 2010; Clark et al., 2014; Burton, 2014). In Spain, a pioneering project on inter-comparison of thermometer screens corresponded to the Spanish-funded SCREEN project coordinated by the Centre of Climate Change (C3; http://www.c3.urv.cat; last accessed 1 November 2014) which assessed the screen bias incorporated into the longest Spanish air temperature records by time-changing thermometric exposures; paired air temperature observations were taken using the old Montsouris stand and modern Stevenson screens (for details see Brunet et al., 2006). However, to our knowledge, no particular research dealing with the impact of different size of Stevenson screens on air temperature has been conducted so far. Only Perry et al. (2007) detected a
Figure 1. (a) Elevation map of the study area showing locations of the Calamocha and Daroca first-order meteorological stations and the supplementary global solar radiation measurements supplied by the Teruel first-order meteorological station. (b) Layout of the Calamocha station with locations of the instrumentation and the medium- and large-sized Stevenson screens.

The novelty of this research lies in quantifying, for the first time, the bias introduced in the time series of air temperature by the two most commonly sized Stevenson screens used by the Spanish Meteorological State Agency (AEMET; http://www.aemet.es/; last accessed 1 November 2014) during last century: the medium-sized Stevenson screen used at the second-order (i.e. thermo-pluviometric) weather stations versus the large-sized Stevenson screen mainly used at the first-order (i.e. complete) meteorological stations.

2. Data and methods

2.1. Trial site

The Aragon Regional Office of the AEMET coordinated this field Stevenson screen intercomparison and the experimental site chosen was located at the first-order meteorological station of Calamocha (AEMET synoptic Id. 08233; 40°55'34''N and 01°17'36''W; 890 m above sea level; and ~150 km from the Mediterranean shore), in a mountainous plateau within the Iberian System Mountains in the northeastern of Spain (Figure 1(a)). This meteorological station represents the continental climatic conditions of most of the inland areas of the Iberian Peninsula. For instance, for...
the 1971–2000 climate normal period the average annual air temperature is 11.0 °C with cold winters (monthly mean air temperature in January is 2.8 °C) and warm summers (July 20.6 °C), and an average annual rainfall of 400.8 mm with the greatest monthly precipitation falling in May and June due to convective storms. Winds are generally weak with maximum wind speeds >10 m s⁻¹ for less than 10% of the days a year. Lastly, the daily average duration of bright sunshine is 7.1 h.

2.2. Stevenson screens, instrumentation and experimental data

Figure 1(b) displays a layout of the Calamocha station with locations of the Stevenson screens and instrumentation. Air temperature, measured in two different sized wooden naturally ventilated Stevenson screens, was intercompared in this experiment. The Stevenson screen is the most common shield used in AEMET’s meteorological station network since the beginning of 20th century (Brunet et al., 2006). The medium Stevenson screen (hereafter Sm) has been the most common radiation shield mainly used at the second-order AEMET’s meteorological station network (90% of stations); internal dimensions are 380 × 450 × 460 mm (width × height × depth; i.e. an inside volume of 0.08 m³). The large Stevenson screen (hereafter Sl) has been basically used at the first-order meteorological stations (10% of stations); internal dimensions are 700 × 730 × 630 mm (width × height × depth; i.e. an inside volume of 0.32 m³). In both screens, a maximum (mercury-filled) and minimum (alcohol-filled) thermometer sets and a psychrometer were mounted 1.5 m above ground level for obtaining daily maximum, minimum and synoptic times (i.e. 0700, 1300 and 1800 UTC) air temperatures. These Thies standard thermometer sets accomplish the WMO requirements (WMO, 2008) with an accuracy of 0.2 °C and a measuring range of −30 to 50 °C. Figure 2 shows the outside and inside of both Stevenson screens with details of the thermometer sets.

Furthermore, daily sunshine hours from a Kipp & Zonen recorder; 10-min averaged intervals wind speed and direction measured at 10 m above the ground, air temperature, relative humidity, precipitation (all Thies sensors), atmospheric pressure (SETRA barotransmitter) data from an automatic weather station (AWS); and cloudiness (in oktas) were also recorded at the Calamocha station. Global solar radiation data were supplied by the closest AWS located in the first-order station of Teruel (AEMET synoptic Id. 08235; 40°21′02″N and 01°07′27″W; 900 m above sea level; and ∼50 km from the Calamocha station). Some of these supplementary meteorological data (i.e. relative humidity, wind speed, total cloud cover, atmospheric pressure and global solar radiation) were used to study the influence on the recorded biases of weather elements (Section 3.2). Moreover, the high-quality air temperature series recorded inside the Sl in the first-order station of Daroca (AEMET synoptic Id. 08157; 41°06′52″N and 01°24′36″W; 779 m above sea level; and ∼30 km from the Calamocha station) was chosen as a reference (i.e. nearby
Overall, we found a positive bias with the all months, with the largest mean (i.e. in daily maximum air temperature between the medium Stevenson screens, which comprises a complete daily dataset of maximum and minimum air temperatures (366 pairs of data) and data series of 156, 121 and 308 pairs of air temperature records at 0700, 1300 and 1800 UTC, respectively. The data gaps at the synoptic times are due to the installation of the AWS in 2011, which generates automatic synoptic reports and therefore manual measurements at the synoptic times are not mandatory for the non-permanent weather observer staff at the Calamocha station, who in turn recorded pairs of air temperatures as much as possible.

3. Results

3.1. Differences in daily maximum and minimum air temperatures

In this section we analyse the biases between maximum and minimum air temperatures measured in both sized Stevenson screens. Table 2 shows monthly statistics of differences ($\Delta T_{\text{max}} = S_{\text{m, max}} - S_{\text{l, max}}$) encountered in daily maximum air temperature between the medium (i.e. $S_{\text{m, max}}$) and the large (i.e. $S_{\text{l, max}}$) Stevenson screens. Overall, we found a positive bias with the $S_{\text{m}}$ measuring higher daily maximum air temperatures than the $S_{\text{l}}$ for all months, with the largest mean $\Delta T_{\text{max}} (>0.50^\circ\text{C})$ during the warm season from May through October, e.g. the greatest mean difference occurred in July with 0.92 $^\circ\text{C}$.

Moreover, mean $\Delta T_{\text{max}}$ were still noticeable (>0.30 $^\circ\text{C}$) during the cold-season from November through April, reaching the lowest mean difference in November with 0.35 $^\circ\text{C}$. On average, the yearly $\Delta T_{\text{max}}$ was 0.54 $^\circ\text{C}$, denoting an overheating of the air inside the $S_{\text{m}}$ in comparison to the $S_{\text{l}}$ throughout the year. The extreme maximum and minimum $\Delta T_{\text{max}}$ show the highest values in summer months (July 1.70 $^\circ\text{C}$) and the lowest ones in winter months (December and January $-0.40$ $^\circ\text{C}$). In addition, the monthly box-and-whisker plots shown in Figure 3(a) also display a noticeable yearly cycle of the $\Delta T_{\text{max}}$, with high biases in summer and low ones in winter months.

Table 3 summarizes monthly statistics of differences ($\Delta T_{\text{min}} = S_{\text{m, min}} - S_{\text{l, min}}$) in daily minimum air temperature between the medium (i.e. $S_{\text{m, min}}$) and large (i.e. $S_{\text{l, min}}$) Stevenson screens. For all months, except for December, we found a slightly negative bias with the mean $\Delta T_{\text{min}}$ lowest in late spring, i.e. May ($-0.19^\circ\text{C}$) and June ($-0.20^\circ\text{C}$). On average the yearly difference between screens is $-0.11^\circ\text{C}$. Therefore, for the minimum air temperatures, biases between both Stevenson screens are lower than the own accuracy of the standard thermometers. The extreme maximum $\Delta T_{\text{min}}$ occurs particularly from November to February (highest in November with 1.0 $^\circ\text{C}$), whereas the extreme minimum $\Delta T_{\text{min}}$ is similar throughout the whole year (lowest in December with $-0.80^\circ\text{C}$). The box-and-whisker plots shown in Figure 3(b) are representative of the negligible $\Delta T_{\text{min}}$, with very low monthly biases, which denote that minimum air temperatures measured in both sized Stevenson screens are similar.

The combined effect of negative bias in $\Delta T_{\text{min}}$ and especially the positive bias in $\Delta T_{\text{max}}$ produced an increase of mean air temperature (Figure 3(c)), with the highest biases in summer (July 0.53 $^\circ\text{C}$) and the lowest in winter months (December 0.16 $^\circ\text{C}$). As a consequence, this effect enhanced the bias in daily air temperature range (Figure 3(d)), with the highest biases in summer (July 1.06 $^\circ\text{C}$) and the lowest in winter months (December 0.33 $^\circ\text{C}$). According to the Student’s $t$-test no statistical significance ($p < 0.05$) was detected when analysing the difference in the paired mean values both at $T_{\text{max}}$ and $T_{\text{min}}$. Nevertheless, nearly significant values in the test were reached at $T_{\text{max}}$ in summer months.
TEMPERATURE MEASUREMENTS ON TWO DIFFERENT SIZED STEVENSON SCREENS

Table 2. Monthly mean, standard deviation and extreme differences in daily maximum air temperatures between the medium- and large-sized Stevenson screens.

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<tbody>
<tr>
<td>Mean</td>
<td>0.42</td>
<td>0.39</td>
<td>0.49</td>
<td>0.42</td>
<td>0.61</td>
<td>0.68</td>
<td>0.92</td>
<td>0.68</td>
<td>0.54</td>
<td>0.65</td>
<td>0.35</td>
<td>0.36</td>
<td>0.54</td>
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<tr>
<td>(\sigma)</td>
<td>0.31</td>
<td>0.29</td>
<td>0.36</td>
<td>0.32</td>
<td>0.30</td>
<td>0.31</td>
<td>0.41</td>
<td>0.33</td>
<td>0.34</td>
<td>0.36</td>
<td>0.34</td>
<td>0.35</td>
<td>0.37</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.90</td>
<td>1.10</td>
<td>1.10</td>
<td>1.00</td>
<td>1.30</td>
<td>1.20</td>
<td>1.70</td>
<td>1.50</td>
<td>1.40</td>
<td>1.30</td>
<td>0.90</td>
<td>1.20</td>
<td>1.70</td>
</tr>
<tr>
<td>Minimum</td>
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<td>−0.10</td>
<td>−0.30</td>
<td>−0.10</td>
<td>0.20</td>
<td>0.00</td>
<td>0.30</td>
<td>0.00</td>
<td>−0.20</td>
<td>−0.10</td>
<td>−0.20</td>
<td>−0.40</td>
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</table>

Figure 3. Monthly box-and-whisker plots of the biases in the (a) maximum, (b) minimum, (c) mean and (d) daily air temperature range measurements between the medium- and large-sized Stevenson screens. The mean (grey line; red in online), the median (black line), the 25th and 75th percentile range (boxes), the 10th and 90th percentiles (whiskers) and the 5th and 95th percentiles (black dots; blue in online) are represented for each month.

3.2. Influence of weather elements on air temperature differences

Table 4 shows that mean air temperature differences (\(\Delta T = S_m - S_l\)) encountered at 0700, 1300 and 1800 UTC were 0.08, 0.51 and 0.11 °C on yearly average, respectively. The monthly mean air temperature differences at 1300 UTC were noticeably above the accuracy of the standard thermometers for all months of the year, whereas at 0700 (except for the summer) and 1800 UTC were always below the accuracy of the

Table 3. Monthly mean, standard deviation and extreme differences in daily minimum air temperatures between the medium- and large-sized Stevenson screens.

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<tbody>
<tr>
<td>Mean</td>
<td>−0.06</td>
<td>−0.02</td>
<td>−0.11</td>
<td>−0.13</td>
<td>−0.19</td>
<td>−0.20</td>
<td>−0.15</td>
<td>−0.13</td>
<td>−0.12</td>
<td>−0.05</td>
<td>−0.14</td>
<td>0.03</td>
<td>−0.11</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>0.26</td>
<td>0.32</td>
<td>0.21</td>
<td>0.23</td>
<td>0.24</td>
<td>0.27</td>
<td>0.25</td>
<td>0.23</td>
<td>0.16</td>
<td>0.10</td>
<td>0.38</td>
<td>0.26</td>
<td>0.26</td>
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<tr>
<td>Maximum</td>
<td>0.60</td>
<td>0.80</td>
<td>0.30</td>
<td>0.40</td>
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<td>0.40</td>
<td>0.40</td>
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<td>0.00</td>
<td>1.00</td>
<td>0.60</td>
<td>1.00</td>
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<tr>
<td>Minimum</td>
<td>−0.60</td>
<td>−0.60</td>
<td>−0.50</td>
<td>−0.50</td>
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thermometers. For this reason, we focused the analysis of the impact of weather elements on $\Delta T$ at 1300 UTC.

Figure 4 shows the relationship between the weather elements and the observed daily $\Delta T$ (i.e. 121 pairs of data) at 1300 UTC; the Pearson’s correlation test was used for statistical analysis. Relative humidity (Figure 4(a)) was negatively ($r = -0.24$) and significantly ($p < 0.01$) correlated with the screen bias, indicating that air temperature differences increase under dry weather conditions. Wind speed (Figure 4(b)) was negatively ($r = -0.25$) and significantly ($p < 0.01$) correlated with the air temperature bias; since both screens are naturally ventilated stronger wind speed enhanced air mixing and minimized the overheating in the medium Stevenson screen. Total cloud cover (Figure 4(c)) also showed a negative ($r = -0.33$) and significant ($p < 0.01$) correlation with the screen bias; e.g. mean $\Delta T$ varied between 0.63 °C on clear sky days (i.e. < 2 oktas) and 0.29 °C on cloudy days (i.e. > 6 oktas). Atmospheric pressure (Figure 4(d)) displayed a positive ($r = 0.26$) and significant ($p < 0.01$) correlation with the air temperature bias, denoting that stable atmospheric conditions tend to increase biases. Lastly, global solar radiation at 1300 UTC (Figure 4(e)) showed a positive ($r = 0.24$) and significant ($p < 0.01$) correlation with $\Delta T$, a relationship that become stronger ($r = 0.43, p < 0.01$) when daily global solar radiation was correlated with daily $\Delta T_{\text{max}}$ for the 366 days (Figure 4(f)). Furthermore, as global solar radiation is higher in spring and summer, this result is consistent with the yearly cycle of the $\Delta T_{\text{max}}$ shown in Figure 3(a). To summarize, anticyclonic weather conditions enhance clear skies, high solar radiation rates, weak winds and low relative humidity values, and this is an atmospheric pattern that reinforces the overheating bias observed in the $S_m$.

3.3. Impact of the size of Stevenson screen on climate series

The overheating bias of the $S_m$ observed at the Calamocha station is evaluated by comparing monthly mean air temperature anomaly series (i.e. as deviations, in °C, from the 1971 to 2000 climate normal period) against those from the nearby first-order station of Daroca (Figure 5). It is noteworthy that monthly mean air temperature anomalies were higher in Calamocha than in Daroca for all months in 2013, in contrast to the previous years (2009–2011) when almost all months were higher in Daroca. Furthermore, the yearly average difference anomalies between both stations in 2009, 2010 and 2011 were −0.21, −0.20 and −0.27 °C, respectively, and increased up to 0.50 °C in 2013.

To adjust the observed bias in maximum air temperatures under the medium-sized Stevenson screen exposure, a linear regression between the daily maximum air temperatures recorded on the $S_m$ ($T_{m_{\text{max}}}$) and the $S_l$ ($T_{l_{\text{max}}}$) was performed. The resulted fitting, not found to be seasonally dependent (not shown), is the following: $T_{l_{\text{max}}} (°\text{C}) = 0.98 T_{m_{\text{max}}} − 0.19$; where all coefficients were significant at $p < 0.01$. This equation corresponds to the maximum air temperature transfer function between $S_m$ and $S_l$ screens in Calamocha. In fact, using this transfer function, if air temperatures had been measured on the $S_m$ instead of the $S_l$ screen, the annual average air temperature for the 1971−2000 climate normal period would have been 11.2 °C, which is 0.2 °C higher than the official series measured inside the $S_l$ screen. The results shown here can have an impact on the Spanish air temperature time series because the high percentage (i.e. ~90%) of stations using the $S_m$.

4. Discussion

In this study we performed a novel experimental design by comparing air temperature measurements recorded inside two different sized Stevenson screens (medium and large, the two types used by the Spanish Meteorological Agency during last century) in the first-order meteorological station of Calamocha, Spain. Although the impact of these two different naturally ventilated wooden shelters was negligible in the differences encountered on daily minimum air temperatures (~0.11 °C on yearly average), it showed a noticeable overheating on daily maximum air temperatures (0.54 °C on yearly average) in the medium-sized Stevenson screen.

We used all synoptic meteorological data available in the regression analysis (i.e. not grouped by season) to represent different weather conditions throughout the year. The inspection of some weather elements revealed that this overheating bias is greatest under stable atmospheric conditions with clear skies, high solar radiation, weak winds and low relative humidity; thus mainly affecting (1) daily maximum temperatures and (2) temperatures recorded at 1300 UTC. Therefore, climate features of Calamocha reinforce the observed overheating during the whole year, particularly in the warm season from May through October. Moreover, the comparison of air temperature anomalies (with respect to the 1971–2000 normal climate period) against the nearby station of Daroca, where no changes in the local environment and Stevenson screen occurred, confirmed the overheating bias introduced by the use of the medium-sized Stevenson screen in Calamocha since 2013. There were no other abrupt changes in the environment that could explain the observed shift in air temperature.
TEMPERATURE MEASUREMENTS ON TWO DIFFERENT SIZED STEVENSON SCREENS

Changes in the dimensions of the instrument shelter can lead to inhomogeneities that may alter the magnitude and sign of long-term trends of air temperature (Vose et al., 1992). The air temperature biases produced by changes in Stevenson screen sizes may introduce non-climatic effects on long-term series and be of interest for some recent published studies dealing with air temperature variability in Spain (Brunet et al., 2007; El Kenawy et al., 2012; Fernández-Montes et al., 2013). Long time series of air temperature often have to be adjusted for inhomogeneities. The transfer equation proposed here could be useful for adjusting daily maximum air temperature series measured under the medium-sized Stevenson screen in nearby second-order or climate-related stations to Calamocha. However, further field experimental intercomparisons are needed to confirm the observed impact of the medium-sized Stevenson screen on the daily maximum temperature measurements, for instance, by reproducing this experiment in other locations with contrasted climate conditions across Spain and obtaining

Figure 4. Scatterplots of the screen air temperature bias (ΔT) in relation to (a) relative humidity, (b) wind speed, (c) total cloud cover, (d) atmospheric pressure and (e) global solar radiation at 1300 UTC, and of the screen maximum air temperature bias (ΔT_{max}) in relation to (f) daily global solar radiation. The Pearson’s correlation coefficient (r), its statistical significance defined at the levels of *p < 0.05 and **p < 0.01, and the number (n) of pairs of data is shown in the upper right corner.

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different transfer functions for each region, or in other countries with National Weather Services using different sized Stevenson shelters. In fact, the impact of screen environment on air temperature measurements is being currently studied by the Met Office (Clark et al., 2014). Additionally, we also suggest further research on other elements of shelters, such as the materials, louvring system, painting or chimney design (i.e. round versus square chimneys), which is a crucial part of the ventilation and has not been investigated yet and could also have an important impact on air temperature measurements.

5. Summary

The main findings of this research are summarized as follows:

1. An overheating of air temperature inside the medium-sized Stevenson screen was detected in comparison to the large-sized Stevenson screen throughout the year. This bias affected daily maximum air temperature records, especially during the warm season (May to October) and at 1300 UTC.

2. The weather conditions enhancing this overheating bias (not statistically significant) are associated with clear skies, high solar radiation rates, weak winds and low relative humidity values.

3. Comparison to nearby station have revealed that the different size of the naturally ventilated wooden Stevenson screens have an impact on mean, maximum and daily air temperature range.

These kinds of investigations are crucial for removing inhomogeneities and accurately assessing the spatio-temporal variability and long-term trends of near-surface air temperature measurements.

Acknowledgements

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TEMPERATURE MEASUREMENTS ON TWO DIFFERENT SIZED STEVENSON SCREENS

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