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Short Communication

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 ~~the~~ 1300 UTC ~~synoptic time~~. 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.*, 2013; Burton, 2014). In ~~the case of~~ Spain, a pioneering project on intercomparison 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

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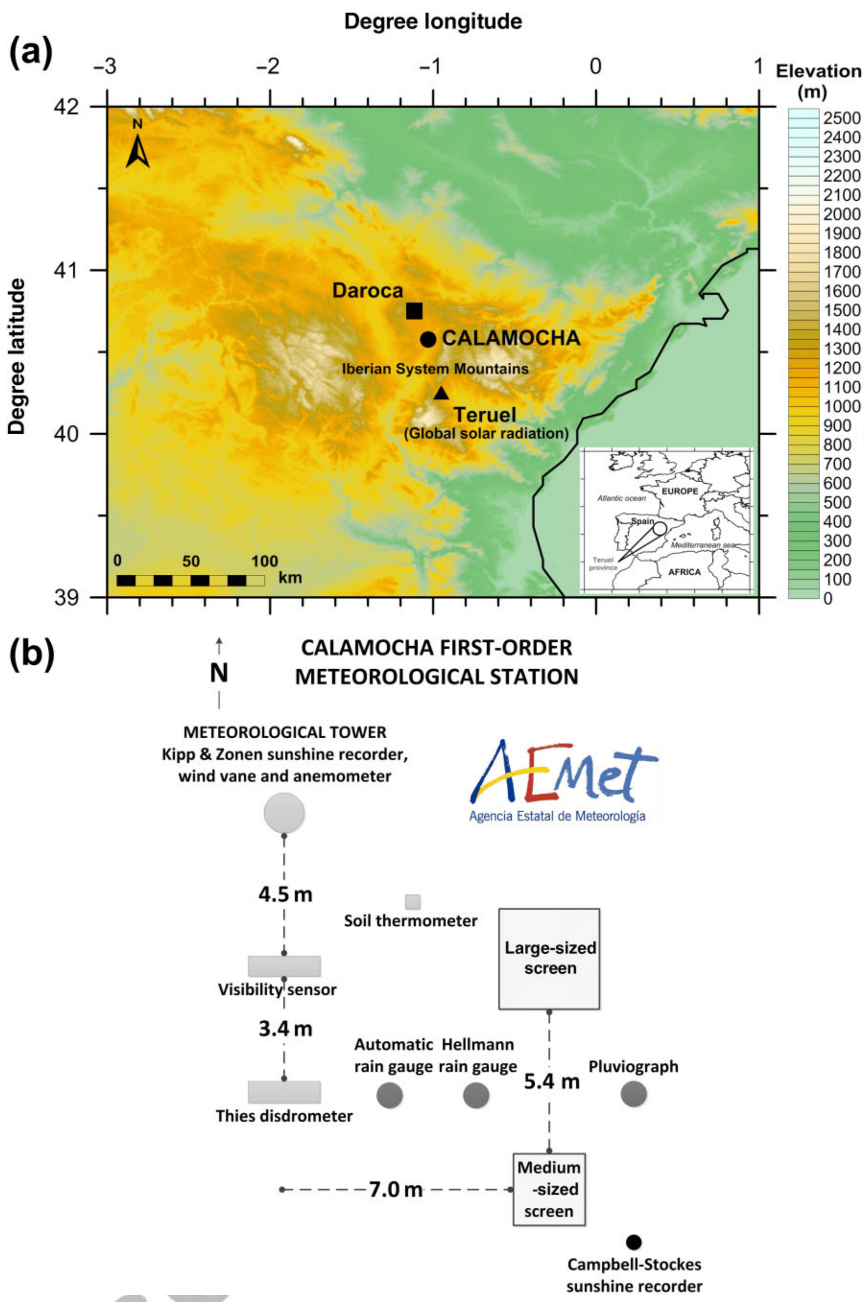

Figure 1. (a) Elevation map of the study area showing locations of the Calamocha and Daroca first-order meteorological stations and the supplementary global solar radiation measurements supplied by the Teruel first-order meteorological station. (b) Layout of the Calamocha station with locations of the instrumentation and the medium- and large-sized Stevenson screens.

slight overheating in the medium Stevenson screen when compared with the large Stevenson screen under high solar radiation conditions.

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 north-eastern 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

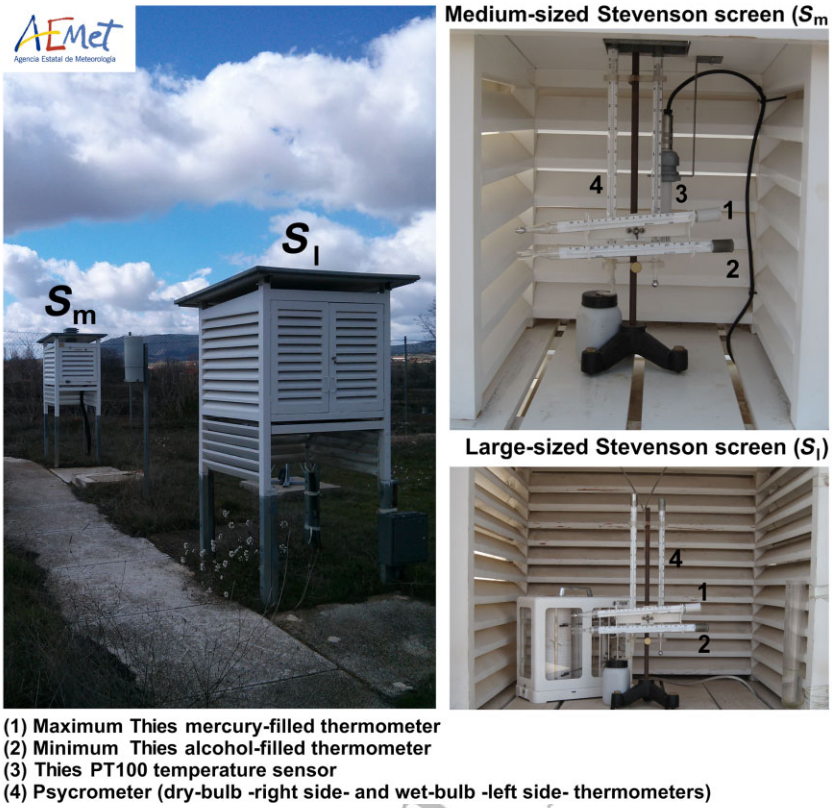

Figure 2. The medium- and large-sized Stevenson screens with the corresponding set of thermomethers used in the field intercomparison at the Calamocha first-order meteorological station.

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 S_m) 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 m^3). The large Stevenson screen (hereafter S_l) 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 m^3). 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. 07, 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 S_l 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

Table 1. Number of pairs of maximum, minimum, 0700, 1300 and 1800 UTC air temperature measurements recorded at both sized Stevenson screens for 1-year period (November 2011 to October 2012).

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Total
Maximum	30	31	31	29	31	30	31	30	31	31	30	31	366
Minimum	30	31	31	29	31	30	31	30	31	31	30	31	366
0700 UTC	27	15	22	18	15	13	8	7	6	7	9	9	156
1300 UTC	9	4	8	9	11	5	14	11	10	13	12	15	121
1800 UTC	28	29	30	21	27	26	24	23	24	23	24	29	308
Total	124	110	122	106	115	104	108	101	102	105	105	115	1317

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

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Mean	0.42	0.39	0.49	0.42	0.61	0.68	0.92	0.68	0.54	0.65	0.35	0.36	0.54
σ	0.31	0.29	0.36	0.32	0.30	0.31	0.41	0.33	0.34	0.36	0.34	0.35	0.37
Maximum	0.90	1.10	1.10	1.00	1.30	1.20	1.70	1.50	1.40	1.30	0.90	1.20	1.70
Minimum	−0.40	−0.10	−0.30	−0.10	0.20	0.00	0.30	0.00	−0.20	−0.10	−0.20	−0.40	−0.40

station) to detect shifts produced in the air temperature time series of Calamocha due to the employment of two different sized Stevenson screens.

Lastly, the compact calibrated Thies PT100 temperature sensor (accuracy 0.1 °C) of the AWS in Calamocha was mounted inside the S_m (see Figure 2) to measure biases against the standard Thies thermometer set; the mean yearly differences between the PT100 sensor and the standard thermometers were 0.08 and −0.03 °C for maximum and minimum air temperatures, respectively, which are below the accuracy of thermometers. This ensures the quality of the intercomparison results shown in this study using data from the standard Thies thermometers in all subsequent sections.

Measurements were carried out by the official weather observer staff at the Calamocha station during 1 year: i.e. from November 2011 to October 2012. Table 1 summarizes the availability of annual and monthly pairs of air temperature measurements (1317 in total) at both the S_m and the S_l 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 ($\Delta T_{max} = S_{m\_max} - S_{l\_max}$) encountered in daily maximum air temperature between the medium (i.e. S_{m_max}) and the large (i.e. S_{l_max}) Stevenson screens. Overall, we found a positive bias with the S_m measuring higher daily maximum air temperatures than the S_l for all months, with the largest mean ΔT_{max} (>0.50 °C) during the warm season from May through October; e.g. the greatest mean difference occurred in July with 0.92 °C. Moreover, mean ΔT_{max} were still noticeable (>0.30 °C) during the cold-season from November through April, reaching the lowest mean difference in November with 0.35 °C. On average, the yearly ΔT_{max} was 0.54 °C, denoting an overheating of the air inside the S_m in comparison to the S_l throughout the year. The extreme maximum and minimum ΔT_{max} show the highest values in summer months (July 1.70 °C) and the lowest ones in winter months (December and January −0.40 °C). In addition, the monthly box-and-whisker plots shown in Figure 3(a) also display a noticeable yearly cycle of the ΔT_{max}, with high biases in summer and low ones in winter months.

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

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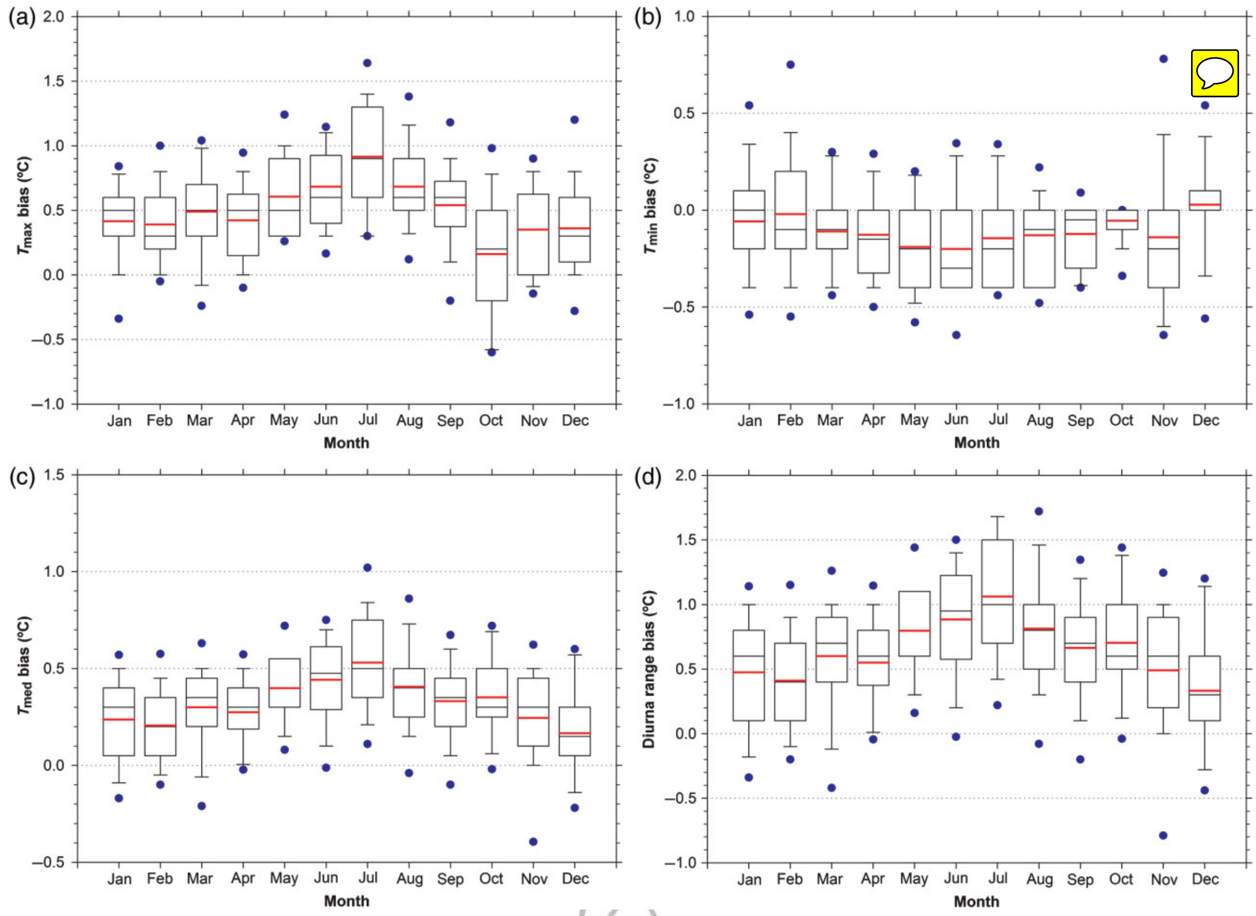

Figure 3. Monthly box-and-whisker plots of the biases in the (a) maximum, (b) minimum, (c) mean and (d) daily air temperature range measurements between the medium- and large-sized Stevenson screens. The mean (grey line), the median (black line), the 25th and 75th percentile range (boxes), the 10th and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

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

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Mean	−0.06	−0.02	−0.11	−0.13	−0.19	−0.20	−0.15	−0.13	−0.12	−0.05	−0.14	0.03	−0.11
σ	0.26	0.32	0.21	0.23	0.24	0.27	0.25	0.23	0.16	0.10	0.38	0.26	0.26
Maximum	0.60	0.80	0.30	0.40	0.20	0.40	0.40	0.40	0.20	0.00	1.00	0.60	1.00
Minimum	−0.60	−0.60	−0.50	−0.50	−0.70	−0.70	−0.50	−0.60	−0.40	−0.40	−0.70	−0.80	−0.80

temperatures measured in both sized Stevenson screens are similar.

The combined effect of negative bias in ΔT_{min} and especially the positive bias in ΔT_{max} produced an increase of mean air temperature (Figure 3(c)), with the highest biases in summer (July 0.53 °C) and the lowest in winter months (December 0.16 °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 °C) and the lowest in winter months (December 0.33 °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_{max} and T_{min}. Nevertheless, nearly significant values in the test were reached at T_{max} in summer months.

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 thermometers. For this reason, we focused the analysis of the impact of weather elements on ΔT at 1300 UTC.

Figure 4 shows the relationship between the weather elements and the observed daily ΔT (i.e. 121 pairs of data) at 1300 UTC; the Pearson's correlation test was used for

Table 4. Monthly mean daily air temperatures differences between the medium- and large-sized Stevenson screens at different synoptic times.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
0700 UTC	−0.01	0.05	0.05	0.05	0.36	0.37	0.50	0.33	0.14	0.01	−0.02	−0.03	0.08
1300 UTC	0.48	0.49	0.68	0.22	0.58	0.45	0.67	0.40	0.46	0.56	0.63	0.25	0.51
1800 UTC	−0.11	−0.09	−0.12	−0.08	−0.11	−0.07	−0.09	−0.17	−0.14	−0.03	−0.16	−0.11	0.11

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 ΔT 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 ΔT, a relationship that become stronger ($r = 0.43$, $p < 0.01$) when daily global solar radiation was correlated with daily ΔT_{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 ΔT_{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. 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_max}) and the S_l (T_{l_max}) was performed. The resulted fitting, not found to be seasonally dependent (not shown), is the following: T_{l_max} (°C) = 0.98 T_{m_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 ~~station~~ 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 ~~the~~ 1300 UTC ~~synoptic time~~. 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 ~~(Figure 5)~~. AQ

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.*

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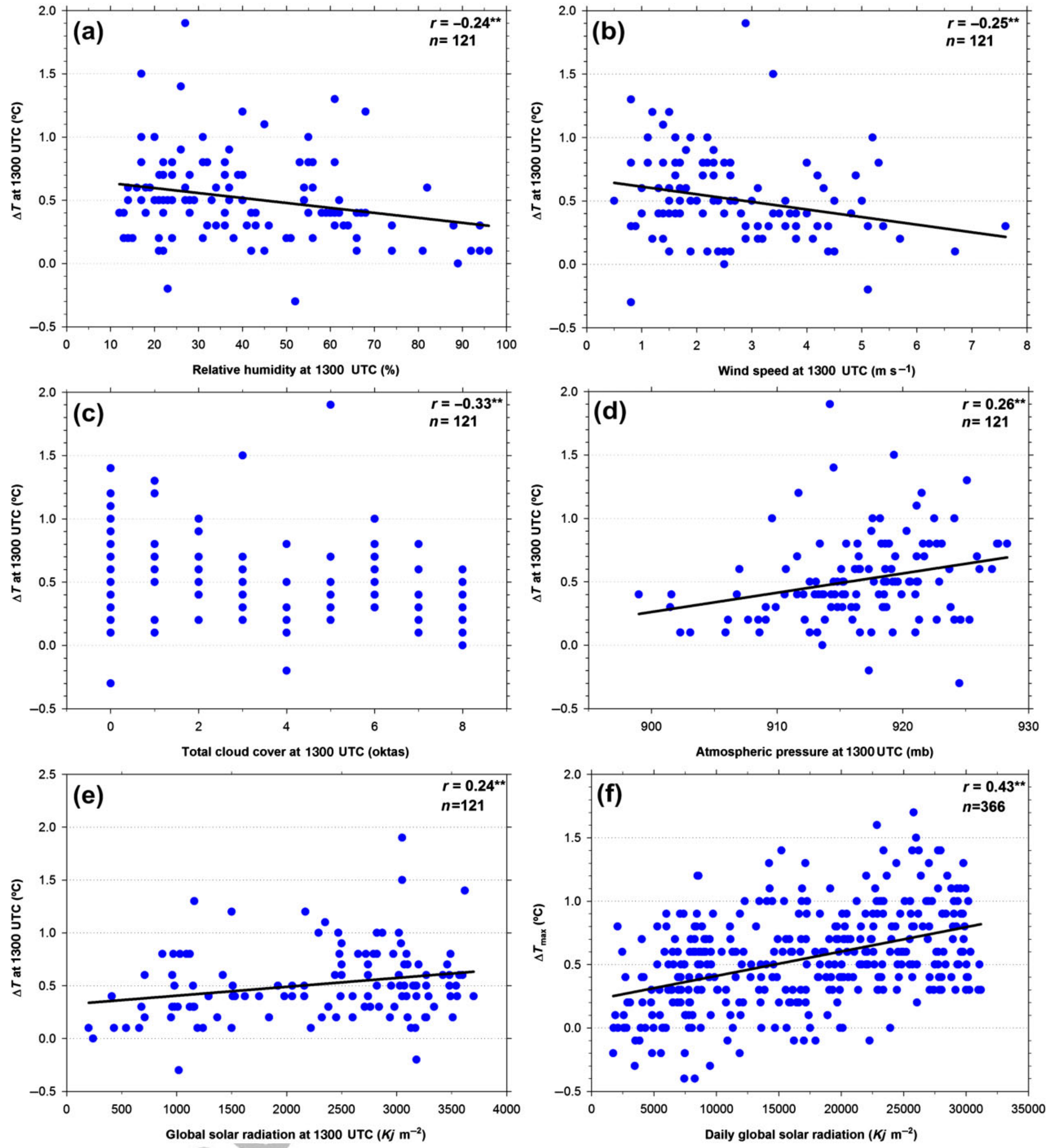

Figure 4. Scatterplots of the screen air temperature bias (ΔT) in relation to (a) relative humidity, (b) wind speed, (c) total cloud cover, (d) atmospheric pressure and (e) global solar radiation at 1300 UTC, and of the screen maximum air temperature bias (ΔT_{max}) in relation to (f) daily global solar 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.

(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 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

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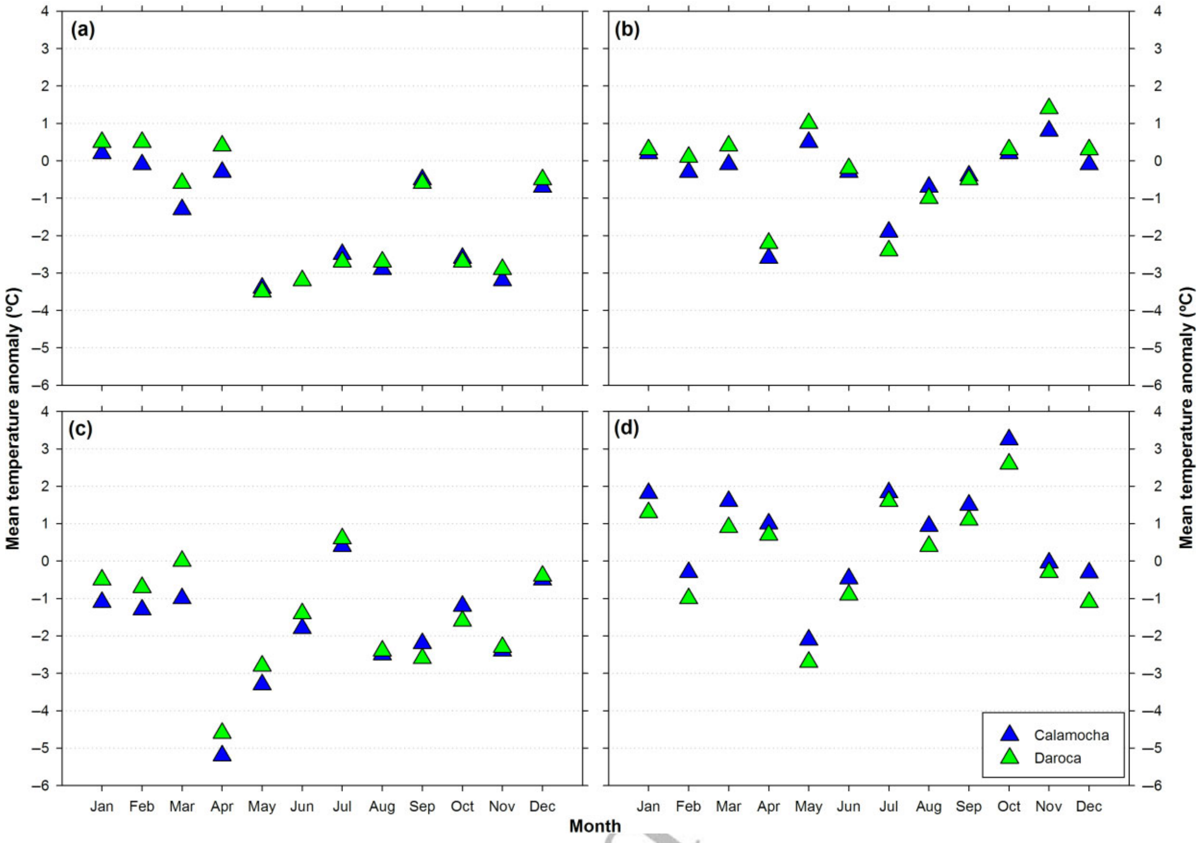

Figure 5. Monthly mean air temperature anomalies with respect to means calculated over the 1971–2000 climate normal period at the Calamocha and the Daroca stations. In (a) 2009, (b) 2010 and (c) 2011, air temperatures were recorded inside a large-sized Stevenson screens at both stations, whereas the medium-sized Stevenson screen was used at Calamocha in (d) 2013. The year 2012 is not shown because the set-up of this intercomparison.

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.

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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 ~~synoptic time~~.
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.

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