Hofer, I.M.J., Hart, A.J., Martín-Vega, D. and HALL, M.J.R. (2020). Estimating crime scene temperatures from nearby meteorological station data. *Forensic Science International*. 306, 110028 (http://dx.doi.org/10.1016/j.forsciint.2019.110028).

Estimating crime scene temperatures from nearby meteorological station data

Abstract

The importance of temperature data in minimum postmortem interval ($_{min}$PMI) estimations in criminal investigations is well known. To maximise the accuracy of $_{min}$PMI estimations, it is imperative to investigate the different components involved in temperature modelling, such as the duration of temperature data logger placement at the crime scene and choice of nearest weather station to compare the crime scene data to. Currently, there is no standardised practice on how long to leave the temperature data logger at the crime scene and the effects of varying logger duration are little known. The choice of the nearest weather station is usually made based on availability and accessibility of data from weather stations in the crime scene vicinity. However, there are no guidelines on what to look for to maximise the comparability of weather station and crime scene temperatures.

Linear regression analysis of scene data with data from weather stations with varying time intervals, distances, altitudes and microclimates showed the greatest goodness of fit (R^2), i.e. the highest compatibility between datasets, after 4-10 days. However, there was no significant improvement in estimation of crime scene temperatures beyond a 5-day regression period. The smaller the distance between scene and weather station and the higher the similarity in environment, such as altitude and geographical area, resulted in greater compatibility between datasets.

Overall, the study demonstrated the complexity of choosing the most comparable weather station to the crime scene, especially because of a high variation in seasonal temperature and numerous influencing factors such as geographical location, urban ‘heat island effect’ and microclimates. Despite subtle differences, for both urban and rural areas an optimal data fit was generally reached after about five consecutive days within a radius of up to 30km of the ‘crime scene’. With increasing distance and differing altitudes, a lower overall data fit was observed, and a diminishing increase in R^2 values was reached after 4-10 consecutive days. These results demonstrate the need for caution regarding distances and climate differences when using weather station data for retrospective regression analyses for estimating temperatures at crime scenes. However, the estimates of scene temperatures from regression analysis were better than simply using the temperatures from the nearest weather station. This study provides recommendations for data logging duration of operation, and a baseline for further research into producing standard guidelines for increasing the accuracy of $_{min}$PMI estimations and, ultimately, greater robustness of forensic entomology evidence in court.

Keywords: Temperature modelling; minimum post-mortem interval; micro-climate; forensic ecology; temperature datalogger

1. Introduction

The potential importance of forensic entomology in criminal investigations of death, to determine a minimum postmortem interval ($_{min}$PMI), i.e. the minimum time since death must have occurred, is undeniable [1, 2, 3, 4, 5, 6]. Insects are poikilothermic and, therefore, the role of temperature in forensic entomology applications, particularly its effects on rates of development, have been well emphasised [e.g. 1, 7, 8, 9]. Temperature is a fundamental influencing factor in body decomposition as well as for estimations of the pre-appearance interval (PAI) in insect succession patterns [7, 10, 11]. Seasonal temperature variations can influence body decomposition rates, as reported by a study in 2004, which found that decomposition rates increased in higher temperatures and with greater rainfall [9]. Temperature ranges can also show variations between different geographical areas, for example between urban and rural areas [12, 13, 14, 15]. While urban and rural areas might not be far apart in terms of distance, the temperatures between those two different environments can vary greatly within the same period, with urban areas being influenced by so-called 'urban heat islands' [14]. Development rates certainly vary between species, but they might also vary within the same species in different geographical areas [15].

Most estimates of $_{min}$PMI based on insect evidence depend at present on the use of developmental data of blow flies (Diptera: Calliphoridae), which are frequently the first insects to colonise cadavers and, therefore, ideal forensic indicators [1, 4]. As mentioned above, the developmental rates of insects, as poikilothermic organisms, are strongly correlated to the environmental temperature. Previous studies showed that a variation of only ±1°C could alter the blow fly development duration by ±5% [15]. This illustrates the importance of accurate temperature data for estimating $_{min}$PMI. Accurate temperature data are not only needed for the reliable application of forensic entomology methods, but also for other disciplines within forensic biology, such as forensic mycology, forensic botany and forensic anthropology decomposition studies. For example, temperature is one of the main factors influencing the growth rates of fungi on dead tissues [16] or the distribution of particular diatom species [17].

The current practice for $_{min}$PMI estimation calculations based on entomological evidence requires three essential components: 1) insect evidence collected from the crime scene/body; 2) temperature data collected at the crime scene after removal of the body; 3) temperature data from the nearest weather station (NWS) to the crime scene. Linear regression analysis of the temperature data from the crime scene with the temperature data from the NWS for a period after body discovery is the key component that enables temperatures to be estimated for the crime scene prior to body discovery and, using those temperature data, the age of insect evidence found at the scene to be estimated. Retrospective estimation of scene temperatures from NWS temperatures is a robust technique that can provide strong correlations in different case scenarios [18, 19]; on the other hand, thermal conditions can sometimes differ greatly within short distances in relation to particular environmental features [7, 20]. Thus, NWS temperature data is an essential factor in the resulting accuracy of these $_{min}$PMI estimations, and it is important to assess the reliability of these data in varying seasonal and geographical conditions [21, 22]. It is important also to consider that the NWS might not provide as good an estimate of scene temperatures as a more distant weather station [23].

In all branches of science, it is important to adhere to a common set of procedures and standards for commonly applied techniques. This is especially so in forensic sciences, such as forensic entomology, due to the legal implications in criminal investigations and the requirement to meet high quality standards with increasing regulation and accreditation. A number of 'best practice' guidelines have already been published, such as those for insect collection, insect preservation and temperature data measurement at the crime scene [1, 2, 24]. However, it is also important to establish best practice guidelines for choosing the most representative NWS to estimate ambient crime scene temperatures as accurately as possible. The accuracy of $_{min}$PMI estimations by forensic entomology methods is strongly dependent on the quality and representativeness of the NWS temperature data used for retrospective corrections [25]. Recently, Charabidze & Hedouin [3] suggested a framework to determine the adequacy of NWS temperature data sets versus the local temperatures experienced by carrion fauna in any particular case scenario. They highlighted potential problems with correction of NWS data according to mathematical models, recommended that forensic entomologists should examine each situation separately to determine whether using temperature estimates is appropriate and concluded that a one-size-fits-all solution is difficult to apply to a complex issue such as forensic meteorology.

To date, there are no standard practice guidelines on how to select the most representative NWS, nor on the minimum temperature data collection period needed at the crime scene in order to achieve optimal linear regression between the crime scene and its NWS. Therefore, the objectives of this study were to determine the suitability of the NWS at varying distances and altitudes from a hypothetical crime scene, including variations between different geographical locations (urban/rural), in estimating actual scene temperatures, as well as the minimum time needed for recording scene temperatures after body discovery to achieve a minimum degree of accuracy in reconstructing scene temperatures prior to discovery. We also looked at the effects of estimating temperatures for one season based on regressions made in another and demonstrate the subtle differences in temperatures that can occur over a short distance due to microclimatic effects.

The results of this study aim to provide guidelines for a standardised minimum duration of crime scene temperature collection as well as recommendations on how to choose the most representative NWS for performing linear regression analysis to estimate $_{min}$PMI. The objective of optimising these components is to increase the accuracy of $_{min}$PMI estimations and, thereby, to increase the reliability of this evidence in legal proceedings [26].

2. Material and Methods

2.1 Exploration of temperature differences between closely adjacent sites

In order to explore the potential for significant differences in temperatures between closely adjacent environments, ground surface temperatures, air temperatures (at 1.0 m above ground in a Stevenson Screen or radiation shield, a Datamate ACS-5050 Weather Shield, Gemini DataLoggers UK Ltd, Chichester West Sussex) and soil temperatures (10 cm depth) were recorded during September to November of 2016 at two sites in the Wildlife Garden of the Natural History Museum [27]. One set of temperature loggers was placed in a small meadow (approximately 15x16 m), labelled ‘Sun’, and the other about 7 m into an area of dense shrubbery shaded by trees, labelled ‘Shade’. The sites were separated by about 17 m on an east-west axis. The most obvious difference between the sites was the higher degree of sunlight in the Sun, although the difference depended on the cloud cover: for example (1) around midday on a sunny day in September there was about 315 times more light in the meadow (Sun:Shade = 67,800:215 lux [luminous flux per unit area]); (2) around midday on a fully overcast day in November there was about 18 times more light in the meadow (Sun:Shade = 3,500:190.5 lux). Light levels were measured using a Heavy Duty HD450 light meter with the sensor oriented vertically upwards at the level of the roof of the Stevenson Screen. It is of significance that the lux levels in the shaded shrubbery on these sunny and overcast days were almost the same, with a difference of only 25 lux.

The six temperature loggers used were all Tinytag or Tinytag Plus2 models produced by

Gemini Data Loggers, two of which were fitted with a thermistor probe. Navarro-Serrano *et al.* [28] found that Tinytag Plus2 loggers gave a robust and constant performance in relation to reference sensors and that the Datamate ACS-5050 weather shield provided good protection over all radiation, wind and snow conditions in their study in a mountainous, snow covered area of Spain. At the end of our Wildlife Garden study, all six loggers were placed into a constant temperature incubator for 10 days. The data for the whole period was downloaded using Tinytag Explorer 4.9, exported to Excel files and then analysed using Unistat 6.0. Although there was a statistically significant difference between the mean temperatures of all of the dataloggers during the incubator trial ($p<0.02$, 2-tailed t-tests, data not shown), the maximum difference between means was only 0.13°C (i.e. 19.81°C versus 19.68°C). This was much smaller than the differences recorded in the Wildlife Garden situations. However, a correction factor was applied to each logger individually so that the means for all loggers over this 10-day calibration period were equalised at 19.74°C. The correction factors varied from -0.073°C to +0.066°C. The hourly data points were then corrected for the Wildlife Garden study and the mean hourly temperatures for 10-day periods in September, October and November 2016 were calculated, together with Standard Deviation (S.D.) and +/- 95% confidence intervals (C.I.) (Table 1).

2.2 Experimental design for weather station study

Hourly temperature data, measured on the hour, from ten UK weather stations (Figure 1), five in an urban and five in a rural area, were acquired from WeatherNet Ltd. (Bournemouth, UK) for the months of January, April and July 2014. These months encompassed all commonly encountered seasonal temperature regimes from winter to summer in the United Kingdom.

One weather station of each dataset, urban and rural, was taken to represent a hypothetical 'crime scene' (CS), and compared to the other four weather stations in the same dataset, categorised as: (1) closest - 12 to 13 km from the CS, (2a) 20 to 30 km from the CS at around the same altitude, (2b) 20 to 30 km away from the CS at an altitude >100 m higher and (3) over 50 km from the CS.

For the urban (U) dataset, the following five weather stations located inside or around London were chosen (Figure 1):

- UCS: St. James's Park, urban 'crime scene', 5 m above mean sea level (MAMSL)
- U1: Kew Gardens:, 6 MAMSL, nearest weather station (NWS)
- U2a: Hampton Waterworks, 12 MAMSL
- U2b: Kenly airfield, 170 MAMSL
- U3: South Farnborough, 65 MAMSL

For the rural (R) dataset, the following five weather stations were chosen in rural areas of the Southeast of England (Figure 1):

- RCS: Goudhurst, rural 'crime scene', 85 MAMSL
- R1: Frittenden, 38 MAMSL, nearest weather station (NWS)
- R2a: Herstmonceaux, West End, 52 MAMSL
- R2b: Wych Cross, 200 MAMSL
- R3: Shoreham airport, 2 MAMSL

2.3 Effect of spatial distance between crime scene and weather station; and of the number of days of temperature recording on the values of R^2 from regression analysis of scene and weather station data

This section of the study investigated both the spatial effect, i.e. linear distance, between the CS and the NWS used for estimating $_{min}$PMI, as well as the effect of variation in duration of logger placement at the CS on the accuracy of that estimation. The latter explored the effect of data richness, i.e. number of data values (hours) collected, on the values of R^2 generated by the linear regressions.

The data were investigated using linear regression analysis to compare temperature data from the UCS (St. James Park) to the four urban weather stations, as well as the RCS (Goudhurst) to the four rural weather stations. In regression analysis, the coefficient of determination R^2, a number between 0 and 1, indicates the goodness of fit of one dataset to another. R^2 values were used here as the comparator statistic to indicate the potential accuracy of temperature estimation. In general, the higher the value of R^2 the better the relationship between two sets of data, but caution is needed in its interpretation. Indeed, Johnson *et al*. [18] concluded that "it is not helpful to inspect the R^2 value as this had no relationship with correlation accuracy".

The analyses were performed over the following consecutive time intervals within each month for the months of January, April and July 2014 on both the Urban and Rural datasets using Unistat 6.0 statistical software, JMP Pro 13 and GraphPad Prism 8.

- 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 25 and 30 days

2.4 Investigation of the phenomenon of high R^2 values for 24-hour periods

In order to investigate the phenomenon of high R^2 values generated by regression analyses of single 24-hour periods, linear regression analysis was used to estimate the mean hourly temperature at the UCS, St. James Park, from two of the nearby urban weather stations, one close by (Kew Gardens, U1) and one distant (South Farnborough, U3). The period estimated was the 10-day period 1st-10th July, i.e. 240 hours. These stations and period were considered to be representative examples within the UK; other combinations were not tested. Regressions were performed for six 1-day periods (1, 6, 11, 16, 21 and 26 July) and six 5-day periods (1-5, 6-10, 11-15, 16-20, 21-25 and 26-30 July).

2.5 Effect of spatial distance between crime scene and weather station; and of the number of days of temperature recording on the estimation of crime scene temperatures from regression analysis of scene and weather station data

The formulae from the linear regression analyses of RCS/UCS versus weather stations, that generated the R^2 values discussed above, were used to estimate scene temperatures and these estimates were then compared with the actual recorded scene temperatures to demonstrate how close to the actual temperatures the estimates were. The effect of both linear spatial distance and temporal distance, i.e. duration of time between body deposition at the crime scene and initiating crime scene temperature collection once the body has been discovered, were investigated.

The period 1st-16th January was selected as the time period of interest for a hypothetical forensic investigation, for example equivalent to a last sighting of the victim on 1st January and discovery of the body on 16th January, with temperatures from 1st-16th January being relevant to insect development on the victim. The mean temperatures at the UCS and the RCS for 1st-16th January were calculated from the data recorded for those sites for that period. Estimates of the mean temperature from 1st-16th January at the UCS and RCS were then calculated based on either a 1-, 5-, 10- or 15-day regression analysis of hourly UCS/RCS versus weather station data for the months of January, April or July, using 1-, 5-, 10- or 15-day intervals within the periods 15th-30th January, 15th-30th

April and 15th-30th July. Selection of the timeframe 1st-16th January enabled the greatest combination of periods after 'body discovery' to be examined, i.e., immediately after recovery and at 3-month and 6-month intervals.

As before, the 'data richness effect' was investigated, here by using regressions of hourly data for 1-, 5-, 10- and 15-day periods. The resulting R^2 values were plotted against the time intervals to determine the minimum amount of time needed to obtain results with the greatest fit.

3. Results and Discussion

3.1 Investigation of temperature differences between closely adjacent sites

The Wildlife Garden temperatures showed a month-on-month decline from the late summer warmth of mid-September to the cool of early winter in mid-November (Table 1). The effect of the location of the loggers, shaded under tree cover versus in full sun in the meadow, was most pronounced in September, when on some sunny days the temperature of the exposed ground level logger in the meadow (Sun 1 surface) reached over 44°C, while the partially sheltered logger in the bushes (Shade 1 surface) always measured below 26°C (Figure 2, Table 1). However, despite the very clear maxima of the Sun surface logger (Figure 2), because the effect of solar radiation occurred over a relatively short period of time each day (Figure 2), there was no statistically significant difference detected between the mean hourly temperatures of any of the Sun loggers in September (Table 1).

In September, the mean temperatures of the Shade loggers were significantly lower than those of the Sun loggers, except for the Sun logger in the Stevenson Screen. However, in the cooler month of October, the ground level and Stevenson Screen temperatures did not differ significantly between Sun and Shade, with the mean soil temperatures in both sites being significantly higher than the air temperatures. In November, mean temperatures were below 10ºC for all loggers. Again, the mean soil temperatures at both sites were significantly higher than the air temperatures, which were not significantly different from one another apart from the Shade ground level temperature (Table 1).

3.2 Effect of spatial distance between crime scene and weather station; and of the number of days of temperature recording on the values of R^2 from regression analysis of scene and weather station data

The mean hourly temperatures at each weather station in each month, together with minimum-maximum ranges, show that all weather stations recorded similar values (Table 2), being located in the same part of South-East England (Figure 1). The January means ranged from 3.0 to 7.3°C, the April means from 10.1 to 12.1°C and the July means from 17.5 to 20.1°C (Table 2).

Our hypothesis was that the closer the weather station was to the crime scene the greater the goodness of fit between the two sets of data (i.e. higher R^2). Similarly, we expected an increase in R^2 with an increased number of data points (hourly temperatures) used in the linear regression analysis, i.e. the available data would be richer due to the longer period of data collection covering a greater range of temperatures.

R^2 values were obtained for both the urban and the rural dataset using linear regression analysis of each of the four weather stations in both datasets against the 'crime scene' stations for thirteen specific time intervals (Figure 3).

The trends of R^2 values were complex but, in general, they rose to a plateau after 4-10 days. The rise either started from an initial low point or from an initial 24-48 hour high point, that was then followed by a decline in R^2 values before the rise to the plateau. This suggests that for the investigated distances, the minimum amount of time needed to reach a maximum goodness of data fit between the weather station used for $_{min}$PMI estimations and the 'crime scene', regardless of distance and altitude differences, would be 4-10 days. This would fit with the period of 5–10 days suggested by Amendt *et al.* [2], and this range would also include the 4–6 days suggested by Haskell *et al.* [20] and the 8 days suggested by Matuszewski and Madra [29] in an urban (Poznan suburbs) environment. However, subsequent comparison of the actual scene temperatures estimated from the models produced by the regression analyses suggested that a minimum period of temperature collection of five days is acceptable (see 3.4).

In general, in both urban and rural settings, and in all seasons, the closest weather station to the UCS or RCS showed the flattest curvilinear pattern out of all four comparisons in either geographical area, while the further the weather station was from the 'crime scene', the more pronounced the curvilinearity (Figure 3). This demonstrates that the closer the weather station used for $_{min}$PMI estimations is to the crime scene, the higher the R^2 values are likely to be, hence the greater the goodness of fit between both datasets and the potentially greater accuracy of the resulting $_{min}$PMI estimations. Within a short distance radius (~15 km), equivalent to the shortest distance studied here, the accuracy of retrospective temperature corrections might not be significantly affected by season, length of correlation period or distance between the crime scene location and the NWS [18].

There was some evidence that the R^2 values of the rural datasets were lower than those of the urban datasets, especially for the weather stations most distant to the RCS. Rural landscapes are often heterogeneous due to the co-existence of different land uses and covers, in contrast to urban areas, which are fairly homogenous other than the contrast between built-up areas and parkland. Large urban areas such as London (UK), might possibly have a more stable macroclimate and less environmental differences than in rural areas, due to the 'urban heat-island effect' [30, 31]. Weather stations associated with predominantly rural land uses or land covers (e.g., farmlands or forests) generally record wider diurnal temperature ranges than those associated with urban related land use or land cover [32]. However, microclimates showing subtle changes in temperatures can be found in all environments (e.g. see 3.1) which could significantly influence the accuracy of $_{min}$PMI estimations.

Dabbs [33] investigated the differences between site-specific and retrospectively collected temperature data from weather stations over periods of one to nine months, approaching a similar question to that posed in this study but for forensic anthropological purposes. The data of Dabbs' study [33] showed that caution should be taken if $_{min}$PMI needs to be estimated over extended time periods (months), which would be applicable for forensic anthropologists, although less relevant to forensic entomologists who generally deal with shorter time periods (days to weeks). Dabbs [33] recommended using weather station data in a radius within 15.3km of the crime scene, except if the microclimate between the crime scene and the weather station differed significantly, in which case the microclimate, not the distance, should be the determining factor in selecting the most appropriate weather station for analysis. The distance to the crime scene is unequivocally an important parameter to be considered in the selection of the weather station, but other parameters such as the elevation or the main type of surrounding vegetation should also been taken into account [3, 7].

3.3 Investigation of the phenomenon of high R^2 values for 24 hour periods

Undertaking a regression analysis using temperature data of only one day often produced high R^2 values (Figure 3), which indicates a good data fit between the two compared weather stations within that 24 hour period. This can be a misleading conclusion however, as data from 24-48 hours, even though it might show a high R^2, is only representative of a relatively short weather period. A period this short will have generally similar temperatures, not representative of the total range of temperatures experienced by the immature stages of flies during their development at a scene.

To explore this further the effect on estimates of mean temperatures from 1-day and 5-day regressions was examined. The mean R^2 values for 1-day regressions were slightly higher than those for 5-day regressions, both for Kew Garden and South Farnborough (Figure 4A). However, when the regression formulae were used to estimate the mean temperatures at St. James Park (actual recorded mean = 17.85ºC), the estimates from the 5-day regressions were marginally more accurate than those from the 1-day regressions and they also showed a smaller degree of variation (measured in 95% C.I.) (Figure 4B). The values of the regression formula constants (c0 and c1) were also less variable in the 5-day regressions (data not shown). Therefore, despite the seemingly good relationship achieved in a 1-day regression, because the day in question might not be representative of temperature variations over longer periods it is better to use a longer interval than 1-day for collecting scene temperatures for use in retrospective regression analysis for crime scene temperature estimation.

3.4 Effect of spatial distance between crime scene and weather station and of the number of days of temperature recording on the estimation of crime scene temperatures from regression analysis of scene and weather station data

Sometimes it is not possible to record scene temperatures during a period immediately after discovery of a body and, therefore, scene estimates have to be based on a relationship with a nearby weather station that might be established in a completely different season with different temperature ranges. These might be hypothesised to result in less accurate estimates of scene temperatures. From our estimation of January scene temperatures based on regressions carried out using data from either January, April and July this hypothesis is largely proven to be true (Figure 5). In fact, the temporal separation between the period to be estimated and the period on which the estimation was made appeared to have a greater and more consistent effect overall than the linear or vertical (altitude) separation between crime scene and weather station (Figure 5). This seasonal effect is probably largely due to temperature differences between the months, which exceeded 5ºC, especially between January and July (Table 2), a critical temperature difference considered by Johnson *et al.* [18] to produce poor estimates.

Considering the urban situation first, looking at estimates of the UCS temperature from the four urban weather stations it is clear that, in general, estimates based on January regressions were better than those based on April or July regressions, when temperatures were generally higher. This was especially apparent when considering estimates based on weather stations U1 and U3. Similarly, the regressions based on 5- to 15-day periods generally gave better estimates of the actual UCS temperatures than from 1-day regressions, supporting the results presented in Figure 4. The 5-day regressions gave an estimate of UCS temperature closer to the actual UCS temperature than did the 1-day regression for 10 of the 12 urban comparisons (i.e. 4 weather stations x 3 months); the estimates were approximately equal for one comparison and the 1-day regression gave a better estimation for one comparison (Figure 5). Overall, there was little difference between estimates from the 5-, 10- and 15-day regressions, suggesting that a 5-day regression is adequate for most situations. However, estimation of climate data is complex and estimations based on a simple linear regression tool do not always produce results that fit the general expectation, e.g. for U2a and U2b estimates from 5- and 10-day periods from July regressions were closer to the actual temperature than estimates from any of the April regressions.

The analysis of the rural sites gives the same general conclusion of improved accuracy of estimation by choosing nearby weather stations in the same season as the crime and for longer than 1-day regression periods but, as with the urban areas, there were exceptions, e.g. the estimations of April regressions were somewhat better than those from January for weather stations R2a and R3. In the rural study the benefit of lengthy temperature data recording periods for regression analysis were less obvious than in the urban setting as, when compared, the 1-day regression and the 5-day regressions each performed better than the other in four comparisons and they were approximately equal in the other four of 12 comparisons (i.e. 4 weather stations x 3 months) (Figure 5).

Of particular interest is that the 5-day regressions provided a mean temperature estimate that was closer to the crime scene mean temperatures than the temperatures of the nearby weather stations (Figure 5, MET), especially for the UCS. Considering that the UCS/RCS and all the weather stations were all standard weather stations with the same placement of recording devices, this is strong support for using a linear regression analysis following placement of a temperature logger at a crime scene, rather than relying on taking the temperatures of the nearest weather station, especially when bodies at crime scenes are often found at covert locations, with an associated microclimate, rather than at locations favoured for weather station placements. Indeed, much effort is expended to ensure that weather stations and their thermometry are placed in standard exposures because of microclimatic effects such as those we observed (see 3.1). Our results contrast with those of Dourel *et al.* [34] who reported no benefit in estimating scene temperatures following a linear regression analysis of scene and nearby weather station data, but their regression analyses were based on a less fine temporal resolution of daily average temperatures rather than the hourly temperatures used here. On the other hand, our results agree with those of Archer [35] who noted that the accuracy of temperature data at a scene was usually improved by correction using retrospective regression analysis as done in this study. Nevertheless, Archer highlighted the need for caution with using correction factors as the technique did not always improve temperature estimates, even in analyses generating high R^2 values [35].

4. Conclusion

The accuracy of estimating crime scene temperatures decreased with increasing distance of the NWS to the crime scene (see 3.2). Similarly, the less data available for performing linear regression analysis to estimate the crime scene temperatures, the poorer was the goodness of fit (R^2) to the crime scene temperatures (‘data richness effect’; see 3.3) and the less accurate were the estimations of actual recorded crime scene temperatures (Figure 5). However, regression analysis of just 24-hour periods can generate high R^2 values, which we believe is mainly due to the small variations in temperature over such periods compared to longer periods. It was demonstrated that longer periods of regression analysis generally resulted in higher R^2 values, following a fall after the initial 24-hour period (Figure 3). However, there is a diminishing return for long periods of regression. The R^2 values did not increase beyond about 4-10 days for the urban and rural studies (Figure 3). The effect of this on estimation of crime scene temperatures suggests that there is no gain in data value by recording scene temperatures for more than about five days (Figure 5).

Overall, this study demonstrated that an appropriate minimum period of data logger placement at the scene of about five days in either urban or rural areas is needed to generate results with a minimum amount of accuracy needed to produce $_{min}$PMI estimations for forensic entomology casework. Although the R^2 values in some areas (Figure 3) suggest that up to a ten-day recording period is required to maximize R^2, the differences in R^2 and regression constants (slope, intercept) between five and ten day regressions were not pronounced. Therefore using an additional five days of limited policing and science resources to maintain the scene for temperature collection is probably not justified. As well as the additional cost, longer recording periods at the scene can result in problems such as the loss of dataloggers through theft or animal interference, and this would lead to a loss in the ability to generate optimal temperature estimates. These results are in good general agreement with those of Johnson *et al*. [18], but our study also covered longer periods of correlation and greater scene to weather station distances. Johnson *et al*. [18] recommended the collection of 10 days' worth of correlation data wherever possible, although they showed little difference between 2, 5 and 10 days correlation. Our results (Figure 5) and those of Archer *et al*. [35] and Johnson *et al*. [18] provide strong support for the use of a regression analysis of scene and NWS temperature data as a method of temperature correction, in contrast to the concerns of Charabidze & Hedouin [3] regarding such methods.

We also demonstrated that mean air and soil temperatures can differ significantly over relatively small distances (17 m in our Wildlife Garden study), and that these differences can vary with seasonal changes. Therefore, determining the placement location of dataloggers at a scene to take account of such microclimates is important. This importance is emphasised by the finding that regression analyses with scene datalogger temperatures generally produced better estimates of scene temperatures than simply taking the temperatures from the nearest weather station as a representative of the crime scene. However, as noted by Charabidze and Hedouin [3], forensic entomologists need to examine each situation individually to determine whether or not the use of an estimated temperature is truly appropriate. For example, if bodies are discovered in the particular microhabitat of containers such as wheeled rubbish bins or suitcases, simple linear regression analysis might not be appropriate [36]. In addition, datalogger placement needs to be considered with care. Weatherbee *et al.* [37] found that accumulated degree hour (ADH) data calculated from nearby weather station temperatures actually fitted better with the observed development of larvae at an experimental scene than ADH data from the microhabitat of the scene did, which was calculated from the temperatures of scene temperature dataloggers, although there was considerable overlap of these ADH ranges. They considered this was due to the dataloggers being placed near to the ground, thereby being exposed to increased radiant and reflective heat and, therefore, higher temperatures than at the weather stations.

A case study previously described by Hofer *et al.* [38] showed that a deviation of estimated crime scene temperatures from the actual crime scene temperatures by only ±0.5°C can alter the $_{min}$PMI estimation by ±1 day, which can be forensically significant in criminal investigations. Those authors also described the difficulty of measuring scene temperatures post-body removal due to a variety of influencing factors, such as direct sunlight, differences between body discovery position and temperature measuring device as well as seasonal differences between winter and summer. Their study recommended that data loggers should be placed at the scene as close to and in as similar conditions as possible to where the body was found. However, they did not consider the optimal period for retrospective temperature data collection at the scene.

Therefore, the results of this study provide an important addition to methods that will increase the reliability not only of forensic entomology applications, but of other branches of forensic ecology that require retrospective estimation of scene temperatures. The study also showed that it is necessary to be cautious with small temperature datasets due to the '24-hour phenomenon', and to be careful of using crime scene temperature data for linear regression analysis from one season to estimate temperatures in another season; high temperature variation might potentially result in increasingly skewed $_{min}$PMI estimations.

5. References

[1] M. Hall, A. Whitaker, C. Richards, Forensic entomology, chapter 8, in: N. Márquez-Grant, J. Roberts (Eds.), Forensic Ecology Handbook: From Crime Scene to Court, 1st ed., Wiley-Blackwell, (2012), pp. 111-140.

[2] J. Amendt, C.P. Campobasso, E. Gaudry, C. Reiter, H.N. LeBlanc, M.J. Hall, Best practice in forensic entomology - standards and guidelines, Int. J. Legal Med. 121 (2007) 90-104.

[3] D. Charabidze, V. Hedouin, Temperature: the weak point of forensic entomology, Int. J. Leg. Med. 133 (2019) 633-639.

[4] J. Amendt, R. Zehner, C.P. Campobasso, C.S. Richards, M.J.R. Hall, Forensic entomology: applications and limitations, Forensic Sci. Med. Pathol., 7 (2011), 379-392.

[5] L.G. Higley, N.H. Haskell, Insect development and forensic entomology, chapter 9, in: J.H. Byrd, J.L. Castner (Eds.), Forensic entomology: The utility of arthropods in legal investigations, 1st ed., CRC Press LLC, 2001, pp. 287-302.

[6] J.H. Byrd, J.L. Castner (Eds.), Forensic entomology: The Utility of Arthropods in Legal Investigations, 1st ed., CRC Press LLC, Boca Raton, FL., 2001.

[7] M. Michalski, J. Nadolski, Thermal conditions in selected urban and semi-natural habitats, important for the forensic entomology, Forensic Sci. Int. 287 (2018) 153-162.

[8] M.J.R Hall, A.P. Whitaker, A.J. Hart, United Kingdom, chapter 9, in Part 2, History, Accomplishments, and Challenges of Forensic Entomology in Europe, in: J. Tomberlin, M. Benbow (Eds.), Forensic Entomology - International Dimensions and Frontiers, 1st ed., CRC Press Taylor & Francis Group, Boca Raton, FL., 2015, pp. 89-99.

[9] M.S. Archer, Rainfall and temperature effects on the decomposition rate of exposed neonatal remains, Sci. Justice 44 (2004) 35-41.

[10] S. Matuszewski, M. Szafalowicz, A. Grzywacz, Temperature-dependent appearance of forensically useful flies on carcasses, Int. J. Legal Med. 128 (2014) 1013-1020.

[11] S. Matuszewski, A. Madra, Factors affecting quality of temperature models for the pre-appearance interval of forensically useful insects, Forensic Sci. Int. 247 (2015) 28-35.

[12] C. Hwang, B.D. Turner, Spatial and temporal variability of necrophagous Diptera from urban to rural areas, Med. Vet. Entomol. 19 (2005) 379–391.

[13] C.C. Hwang, B.D. Turner, Small-scaled geographical variation in life-history traits of the blowfly *Calliphora vicina* between rural and urban populations, Entomologia Experimentalis et Applicata 132 (2009) 218-224.

[14] R.L. Wilby, P.D. Jones, D.H. Lister, Decadal variations in the nocturnal heat island of London, Weather 66 (2011) 59-64.

[15] S.E. Donovan, M.J. Hall, B.D. Turner, C.B. Moncrieff, Larval growth rates of the blowfly, Calliphora vicina, over a range of temperatures, Med. Vet. Entomol. 20 (2006) 106-114.

[16] D.L. Hawksworth, P.E.J. Wiltshire, Forensic mycology: the use of fungi in criminal investigations, Forensic Sci. Int. 206 (2011) 1–11.

[17] K.A. Zimmerman, J.R. Wallace, The potential to determine a postmortem submersion

interval based on algal/diatom diversity on decomposing mammalian carcasses in brackish ponds in Delaware, J. Forensic Sci. 53 (2008) 935–941.

[18] A.P. Johnson, F.J. Wallman, M.S. Archer, Experimental and casework validation of ambient temperature corrections in forensic entomology, J. Forensic Sci. 57 (2012) 215–21.

[19] S. Matuszewski, A. Mądra-Bielewicz, Post-mortem interval estimation based on insect evidence in a quasi-indoor habitat, Sci. Justice 59 (2019) 109-115.

[20] N.H. Haskell, W.D. Lord, J.H. Byrd, Collection of entomological evidence during death investigations, in: J.H. Byrd, J.L. Castner (eds.) Forensic entomology: the utility of arthropods in legal investigations, CRC Press LLC, Boca Raton, 2001, 81–120.

[21] M. Archer, Comparative analysis of insect succession data from Victoria (Australia) using summary statistics versus preceding mean ambient temperature models, J. Forensic Sci. 59 (2014) 404-412.

[22] T.H. Chua, 2013. Use of temperature model in estimating postmortem interval in forensic entomology, Int. J. Entomol. Res. 1 (2013) 11-15.

[23] G.R. Dabbs, Caution! All data are not created equal: The hazards of using National Weather Service data for calculating accumulated degree days, For. Sci. Int. 202 (2010) 49-52.

[24] J. Amendt, G. Anderson, C.P. Campobasso, I. Dadour, E. Gaudry, M.J.R. Hall, T.C. Moretti, K.L. Sukontason, M.H. Villet, Standard Practices, chapter 9, in: J. Tomberlin, M. Benbow (Eds.), Forensic Entomology - International Dimensions and Frontiers, 1st ed., CRC Press Taylor & Francis Group, Boca Raton, FL., 2015, pp. 381-398.

[25] S. Matuszewski, A. Mądra-Bielewicz, Validation of temperature methods for the estimation of pre-appearance interval in carrion insects, Forensic Sci. Med. Pathol. 12 (2016) 50–57.

[26] G. Moreau, J.P. Michaud, K.G. Schoenly, Experimental design, inferential statistic, and computer modelling, chapter 19, in: J.K. Tomberlin, M.E. Benbow (Eds.), Forensic entomology: International dimensions and frontiers, 1st ed., Taylor & Francis Group, Boca Raton, FL., 2015, pp. 205-229.

[27] C. Ware, M. Lowe, D. Sivell, A. Baker, T. Bantock, M. Barclay, G. Carr, L. Cooper, L. Ellis, M.J.R. Hall, E. Hollowday, D.M. Honey, D. John, J. Martin, D. Notton, D. Osborne, A. Rundle, E. Sherlock, B. Tabor, T.J. Thomas, H. Thüs, J. Tovey, P. Wolseley, Further developments of the flora and fauna of the Wildlife Garden at the Natural History Museum, London –Twenty years of species recording, The London Naturalist 95 (2016) 45-159.

[28] F. Navarro-Serrano, J.I. López-Moreno, C. Azorin-Molina, S. Buisán, F. Domínguez-Castro, A. Sanmigual-Vallelado, E. Alonso-González, M. Khorchani, Air temperature measurements using autonomous self-recording dataloggers in mountainous and snow covered areas, Atmos. Res. 224 (2019) 168-179.

[29] S. Matuszewski, A. Mądra-Bielewicz, Post-mortem interval estimation based on insect evidence in a quasi-indoor habitat, Sci. Justice 59 (2019) 109-115.

[30] R.L. Wilby, P.D. Jones, D.H. Lister, Decadal variations in the nocturnal heat island of London, Weather 66 (2011) 59-64.

[31] World Weather and Climate Information 2015. Average minimum and maximum

temperatures in London, United Kingdom, over the year. [ONLINE] Available: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,London,United-Kingdom [Accessed: December 12th, 2015].

[32] K.P. Gallo, D.R. Easterling, T.C. Peterson, The influence of land use/land cover on climatological values of the diurnal temperature range, J. Clim. 9 (1996) 2941–2944.

[33] G.R. Dabbs, How should forensic anthropologists correct national weather service temperature data for use in estimating the postmortem interval?, J. Forensic Sci. 60 (2015) 581-587.

[34] L. Dourel, T. Pasquerault, E. Gaudry, B. Vincent, Using Estimated On-Site Ambient Temperature Has Uncertain Benefit When Estimating Postmortem Interval, Psyche 2010 (2010) 1-7.

[35] M.S. Archer, The effect of time after body discovery on the accuracy of retrospective weather station ambient temperature corrections in forensic entomology, J. Forensic Sci. 49 (2004) 553-559.

[36] G. Moreau, L. Lutz, J. Amendt, Honey, can you take out the garbage can? Modelling weather data for cadavers found within containers, Pure Appl. Geophys. (2019) 1-12.

[37] C.R. Weatherbee, J.L. Pechal, T. Stamper, M.E. Benbow, Post-Colonization Interval Estimates Using Multi-Species Calliphoridae Larval Masses and Spatially Distinct Temperature Data Sets: A Case Study, Insects 8 (2017) 40.

[38] I.M.J. Hofer, A.J. Hart, D. Martín-Vega, M.J.R. Hall, Optimising crime scene temperature collection for forensic entomology casework, Forensic Sci. Int. 270 (2017) 129-138.

Table 1: Mean Wildlife Garden temperatures (°C ±95% CI from t-intervals) during the periods indicated to show the seasonal decline from September through October to November 2016. Location (Shade or Sun) and type of temperature datalogger (ground level, Stevenson screen or 10 cm deep soil probe) is indicated. Mean temperatures with a different letter within a month (September, October or November) are statistically significantly different, those with the same letter are not significantly different (p-value<0.05).

Datalogger	Mean temp [°C]	SD ±°C	95% CI		Range [°C]	
			Lower	Upper	Minimum	Maximum
05-14 September						
Shade ground level	18.78 A	2.6827	18.44	19.12	11.65	25.52
Shade St-Screen	19.47 AC	3.3115	19.05	19.90	11.15	29.02
Shade soil probe	17.37 B	0.8579	17.26	17.48	15.67	18.98
Sun ground level	19.90 C	4.7052	19.30	20.50	12.14	44.81
Sun St-Screen	20.10 C	3.9227	19.60	20.60	10.80	32.87
Sun soil probe	19.82 C	0.9269	19.71	19.94	18.09	22.47
05-14 October						
Shade ground level	11.96 A	1.2625	11.80	12.12	8.80	14.27
Shade St-Screen	12.24 A	1.8042	12.01	12.47	7.95	15.64
Shade soil probe	13.00 B	0.6078	12.92	13.08	11.79	14.26
Sun ground level	12.43 A	2.5017	12.11	12.75	7.83	25.62
Sun St-Screen	12.36 A	2.0735	12.09	12.62	7.25	17.47
Sun soil probe	14.54 C	0.5116	14.47	14.60	13.46	15.73
05-14 November						
Shade ground level	7.51 A	1.3905	7.33	7.68	4.28	11.23
Shade St-Screen	6.77 B	2.1113	6.50	7.04	1.48	12.00
Shade soil probe	9.25 C	0.5775	9.17	9.32	8.24	10.74
Sun ground level	7.05 B	1.7491	6.83	7.27	3.20	11.22
Sun St-Screen	7.00 B	2.3273	6.71	7.30	1.17	12.64
Sun soil probe	9.45 D	0.6117	9.37	9.53	8.59	11.26

Table 2: Mean hourly temperatures (with minimum to maximum range in brackets) during the months of January (n = 744 hours), April (n = 720) and July (n = 744) 2014, for the hypothetical urban (UCS) and rural (RCS) crime scenes and for each of the four urban (U1-3) and rural (R1-3) weather stations.

Location	January [°C]	April [°C]	July [°C]
UCS (St James Park)	7.3 (1.2 - 12.7)	12.1 (5.4 - 19.9)	20.1 (11.5 - 31.7)
U1 (Kew Gardens)	6.5 (-2.5 – 12.5)	11.2 (1.0 – 19.4)	19.8 (8.6 – 29.7)
U2a (Hampton Waterworks)	7.0 (-0.9 – 12.3)	11.4 (3.5 - 18.8)	19.6 (10.9 - 29.1)
U2b (Kenley Airfield)	5.9 (-0.8 – 12.0)	10.2 (1.6 – 18.5)	18.0 (8.5 – 27.0)
U3 (South Farnborough)	3.0 (-3.6 – 12.3)	10.4 (-0.1 – 18.4)	18.6 (7.5 - 27.7)
RCS (Goudhurst)	6.4 (-2.4 – 12.2)	10.5 (-0.2 – 19.3)	18.0 (6.5 – 28.3)
R1 (Frittenden)	6.6 (-3.2 – 12.6)	10.7 (0.6 – 20.5)	18.3 (6.5 – 30.2)
R2a (Herstmonceaux)	6.9 (-0.3 – 12.4)	10.7 (2.1 – 19.7)	18.2 (8.9-27.8)
R2b (Wych Cross)	6.0 (-0.2 – 11.3)	10.1 (2.9 - 17.9)	17.5 (9.9 – 26.4)
R3 (Shoreham Airport)	7.2 (-1.2 – 11.7)	10.4 (0.3 – 18.2)	18.2 (8.4 – 28.2)

Figure Legends

Figure 1: Location of urban and rural WeatherNet weather stations in the southeast of England, United Kingdom.

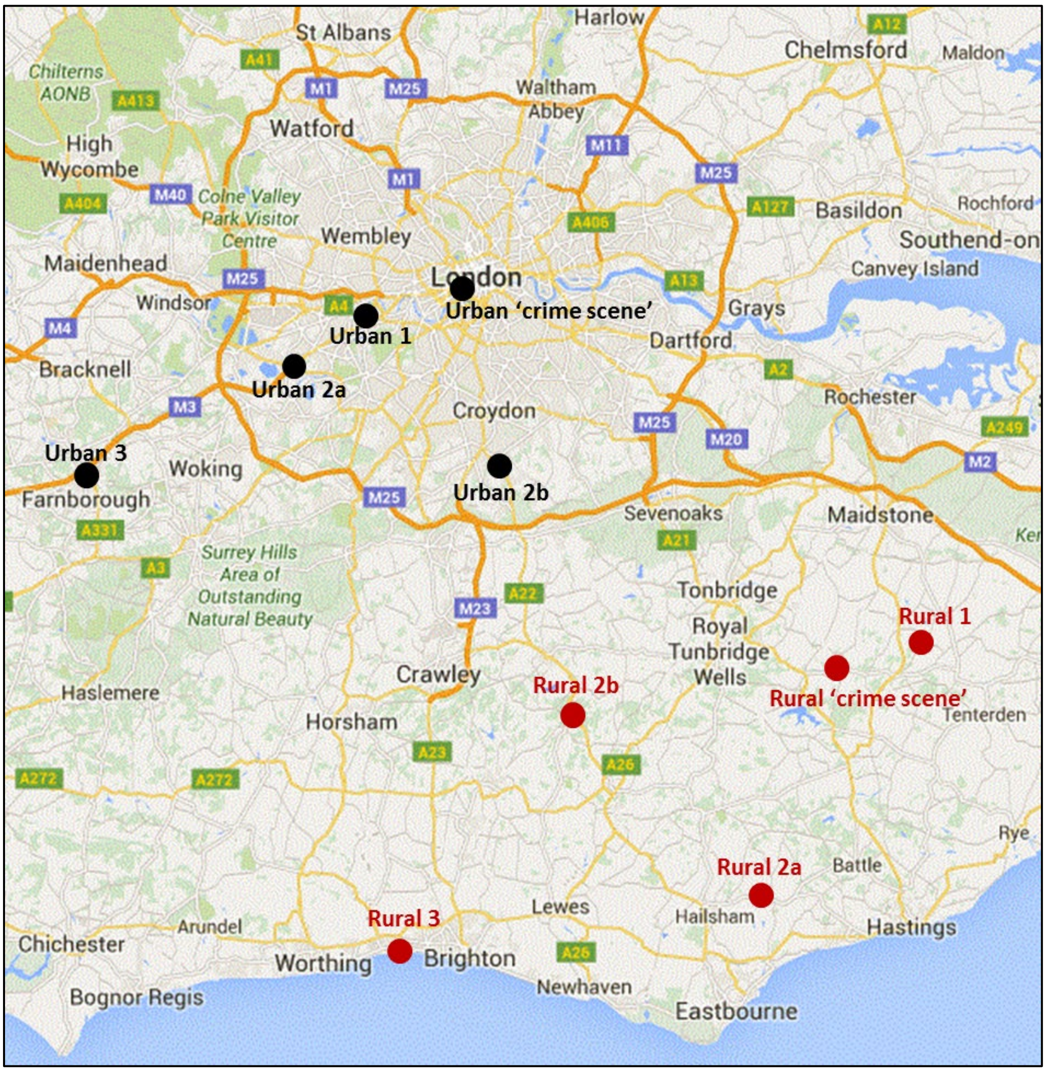
Figure 2: Hourly temperatures (°C) for the six temperature loggers placed in the Wildlife Garden at the Natural History Museum from 05-14 September 2016. Dates on the x-axis are placed at midday, 12:00 hours BST. The darker colour lines are data from loggers in the shade, the lighter colour lines from loggers in the sun: soil surface (blue); Stevenson Screen (green); 10cm deep soil probe (brown).

Figure 3: Plotted graphs of obtained R^2 values of the urban (upper) and rural (lower) datasets using linear regression analysis, against the following chosen time intervals in the months of January (A), April (B) and July (C) 2014: 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 25 and 30 days.

Figure 4: Data from linear regression analysis of St. James Park (urban crime scene, UCS) temperature data against either Kew Gardens (U1) or South Farnborough (U3) temperatures in July, showing: A) values of R^2 from either 1-day or 5-day regressions; B) estimates of St James temperatures from either 1-day or 5-day regressions (n=6 in all analyses, mean of means ±95% CI plotted).

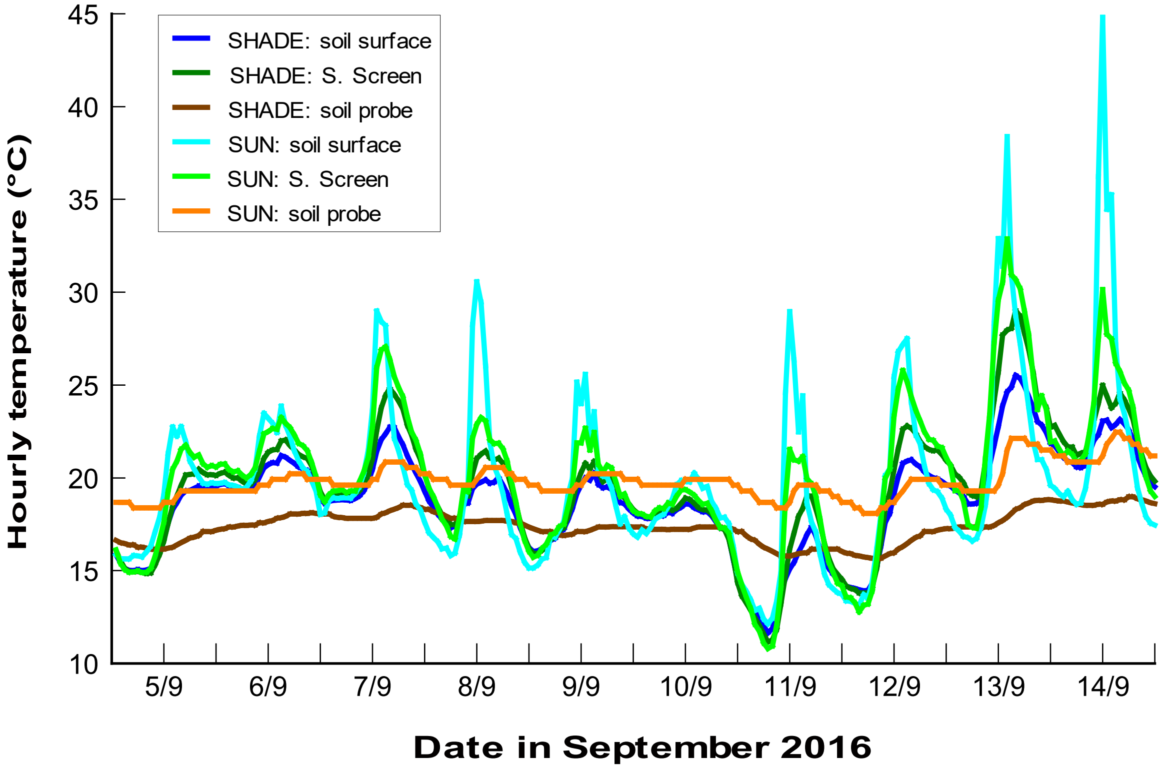
Figure 5: Estimations of Urban Crime Scene (UCS, left column) and Rural Crime Scene (RCS, right column) temperatures from Urban and Rural weather stations, respectively. Each of the eight graphs shows on the left-hand side the mean hourly temperature for the period 1st-16th January for the UCS or RCS together with the mean hourly temperature for the nearby weather station (indicated as MET), either Urban or Rural 1, 2a, 2b or 3. Each graph also shows three sets of four points representing the estimate of the mean temperature for the UCS or RCS for the period 1st-16th January based on either a 1, 5, 10 or 15-day regression analysis of UCS or RCS versus weather station data for the months of January, April or July using 1, 5, 10 or 15-days within the periods 15-30 January, 15-30 April and 15-30 July. Bars indicate ±95% CI and the two horizontal lines show those limits for the actual UCS or RCS data for the period 1st-16th January.

Figure 1:



Urban 'crime scene'
Urban 1
Urban 2a
Urban 2b
Urban 3
Rural 'crime scene'
Rural 1
Rural 2a
Rural 2b
Rural 3
London
St Albans
Harlow
Chelmsford
Maldon
Watford
Waltham Abbey
High Wycombe
Chilterns AONB
Colne Valley Park Visitor Centre
Wembley
Basildon
Rochford
Southend-on
Canvey Island
Maidenhead
Windsor
Grays
Dartford
Bracknell
Rochester
Croydon
Woking
Farnborough
Sevenoaks
Maidstone
Surrey Hills Area of Outstanding Natural Beauty
Tonbridge
Royal Tunbridge Wells
Crawley
Haslemere
Horsham
Tenterden
Rye
Battle
Lewes
Hailsham
Hastings
Chichester
Arundel
Worthing
Brighton
Newhaven
Eastbourne
Bognor Regis

Figure 2:



SHADE: soil surface
SHADE: S. Screen
SHADE: soil probe
SUN: soil surface
SUN: S. Screen
SUN: soil probe
Hourly temperature (°C)
45
40
35
30
25
20
15
10
5/9
6/9
7/9
8/9
9/9
10/9
11/9
12/9
13/9
14/9
Date in September 2016

Figure 3A:

January 2014

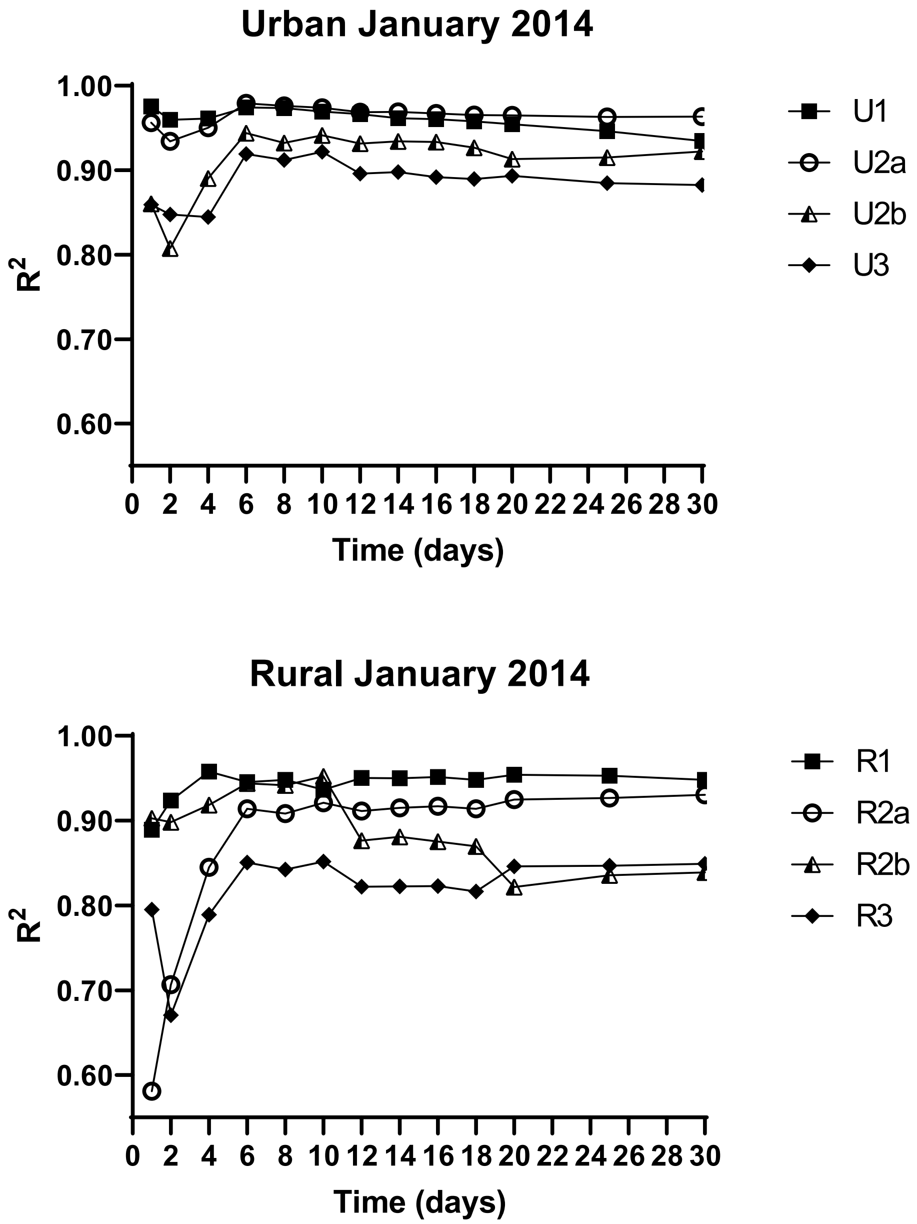


Figure 3B:

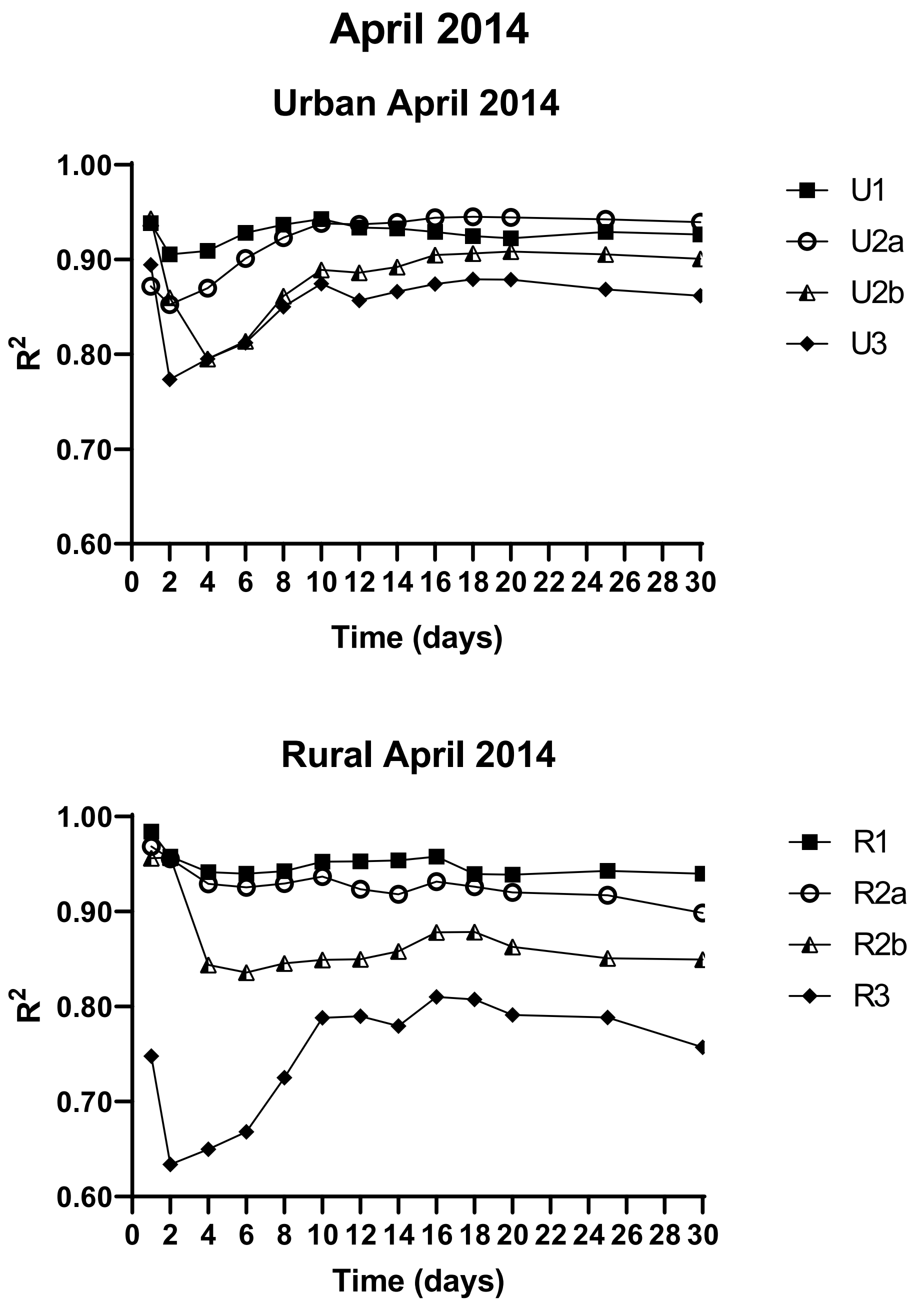

April 2014
Urban April 2014
1.00
0.90
0.80
0.70
0.60
R^2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Time (days)
U1
U2a
U2b
U3
Rural April 2014
1.00
0.90
0.80
0.70
0.60
R^2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Time (days)
R1
R2a
R2b
R3

Figure 3C:

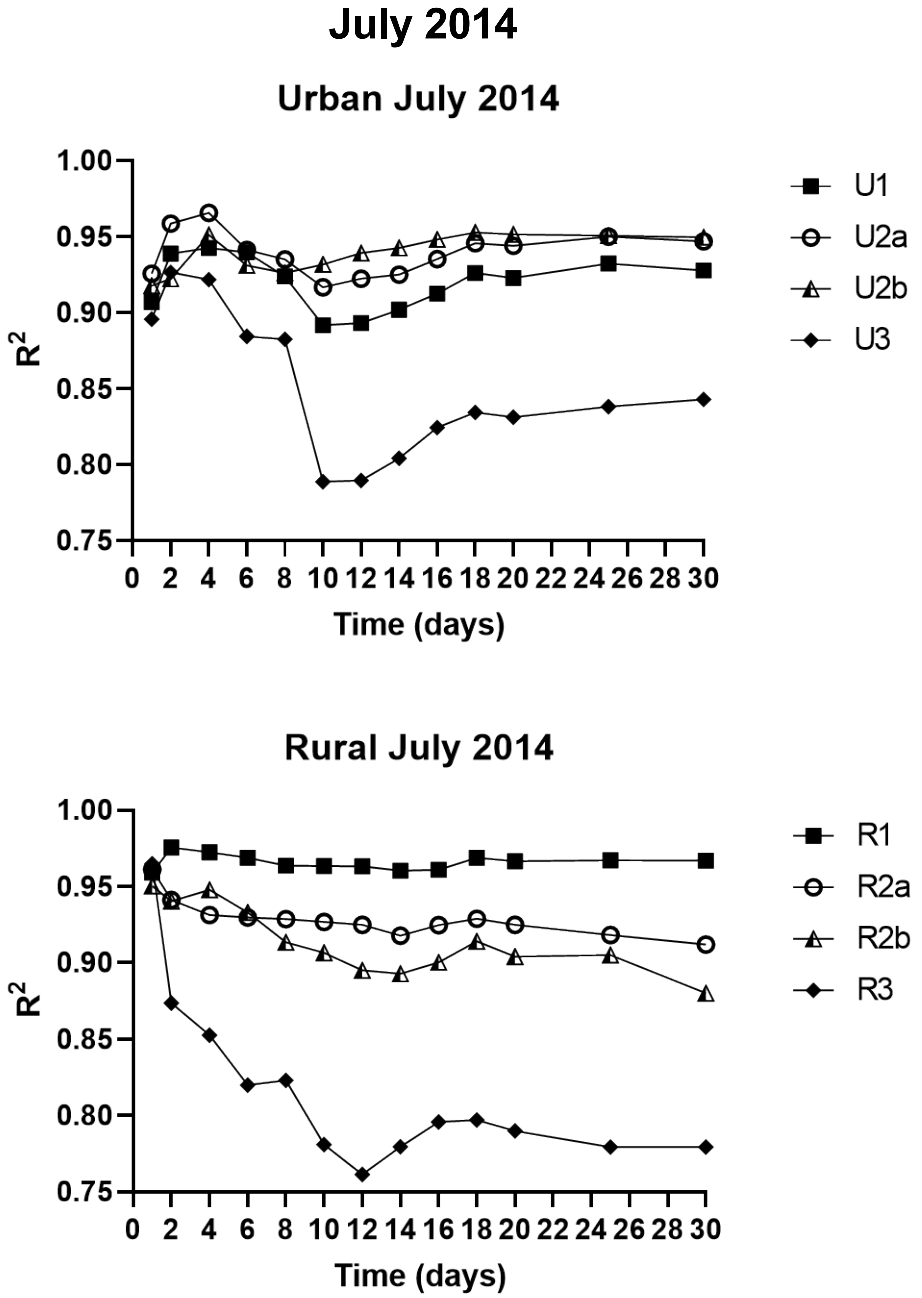

July 2014
Urban July 2014
1.00
0.95
0.90
0.85
0.80
0.75
R2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Time (days)
U1
U2a
U2b
U3
Rural July 2014
1.00
0.95
0.90
0.85
0.80
0.75
R2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Time (days)
R1
R2a
R2b
R3

Figure 4:

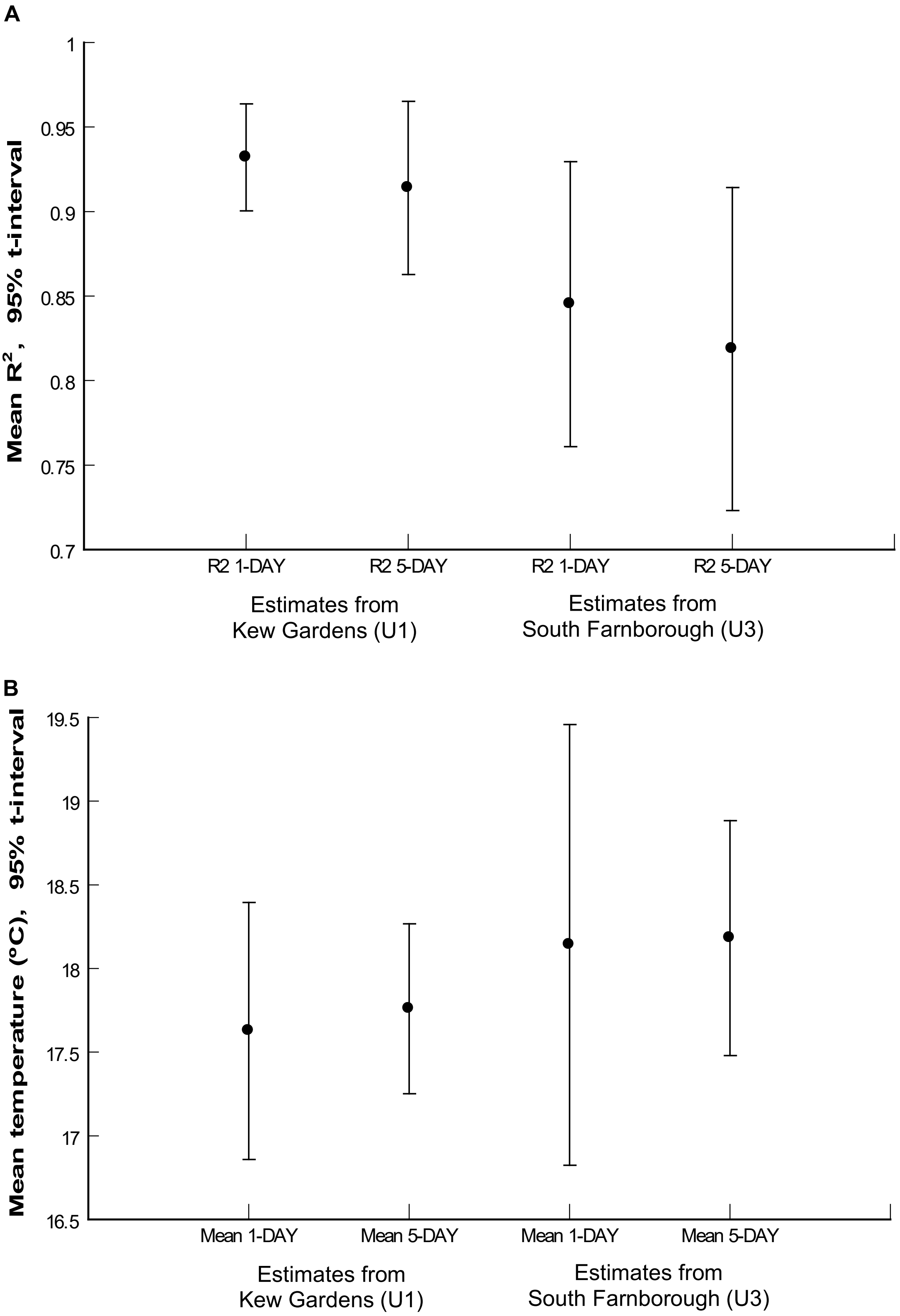
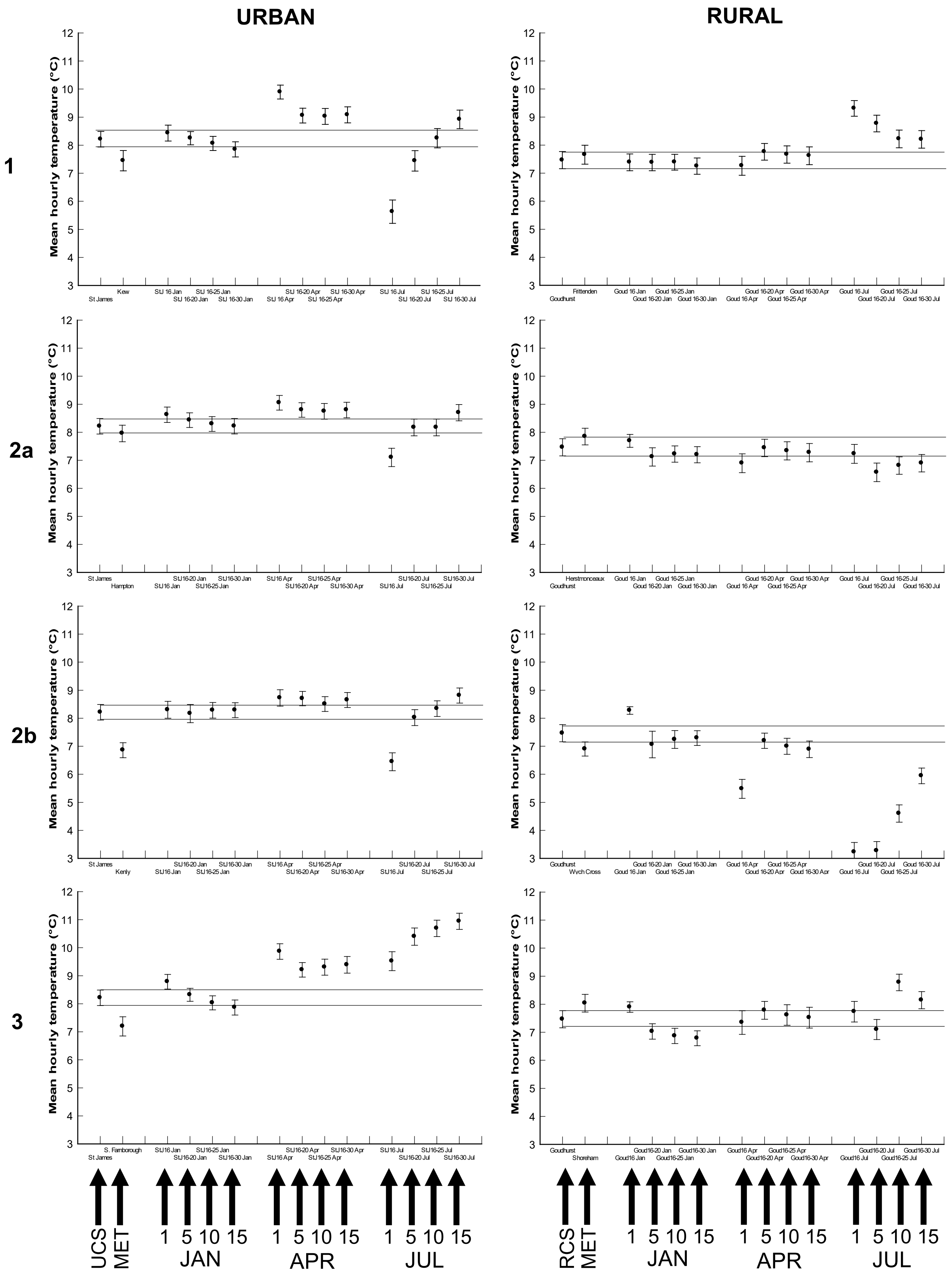

A
Mean R², 95% t-interval
1
0.95
0.9
0.85
0.8
0.75
0.7
R2 1-DAY
R2 5-DAY
R2 1-DAY
R2 5-DAY
Estimates from Kew Gardens (U1)
Estimates from South Farnborough (U3)
B
Mean temperature (°C), 95% t-interval
19.5
19
18.5
18
17.5
17
16.5
Mean 1-DAY
Mean 5-DAY
Mean 1-DAY
Mean 5-DAY
Estimates from Kew Gardens (U1)
Estimates from South Farnborough (U3)

Figure 5:


URBAN
RURAL
1
2a
2b
3
Mean hourly temperature (°C)
UCS
MET
RCS
1 5 10 15
JAN
APR
JUL