Generating near-extreme Summer Reference Years (SRY) for building performance simulation

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Abstract

At present there is no universally accepted method for deriving near-extreme summer weather data for building performance simulation. Existing datasets such as the Design Summer Years (DSY) used in the United Kingdom (UK) to estimate summer discomfort in naturally ventilated and free running buildings have been criticised for being inconsistent with the corresponding Test Reference Years (TRY). This paper proposes a method for generating Summer Reference Years (SRY) by adjusting the TRY of a given site with meteorological data in order to represent near-extreme conditions. It takes as the starting point that the TRY is robust, being determined on a monthly basis from the most typical months. Initial simulations for the 14 UK TRY locations show promising results for determining building overheating with the SRY.

Practical application: The proposed method for deriving near-extreme summer years from multi-year data and the corresponding 'typical' weather year (TRY) of a given site is applicable to locations worldwide and facilitates summer overheating assessment of naturally ventilated and free running buildings. The method helps to overcome the previous shortcomings of near-extreme summer year selection procedures by providing a clear relationship to the underlying TRY.

Keywords

Weather data, near-extreme summer, design summer year, summer reference year, summer overheating

Introduction

Assessing the performance of building services systems at a given location through building performance simulation generally requires weather data series representing a 'typical' year, such as the Test Reference Years (TRY) commonly used in Europe, for example the United Kingdom (UK) [1,2] and Germany [3], the Typical Meteorological Years (TMY) used in the United States (U.S.) [4] or the Design Reference Years (DRY) as, for example, used in Denmark [5,6]. Such data series are available for worldwide locations in a range of different file formats [7,8,9]. They are usually composed of individual months that are derived from a multi-year data set by using statistical methods, most commonly the Finkelstein-Schafer statistic [10]. This statistic compares the cumulative distribution functions of various climate parameters in order to identify the most 'typical' months out of the multi-year data. Parameters that are considered are generally: dry bulb temperature, solar irradiation / cloud cover, humidity and / or wind speed. Common data generation methods using the Finkelstein-Schafer statistic are the Sandia method [4] and the ISO method [11], but other approaches also exist. For example, the UK TRYs have been derived by using the Finkelstein-Schafer statistic, yet by applying a different combination of climate parameters and different weightings for determining the candidate months compared to the above two methods [2].

Besides using the Finkelstein-Schafer statistic there are a range of other data selection methods. The 'Danish' DRY method [5] for instance uses a combination of a climatological evaluation and a mathematical selection procedure in order to identify the most 'typical' months, looking at a range of climate parameters. A different approach was taken in Germany where only the hourly mean dry bulb temperature and its variance in relation to the long-term means are considered for the TRY selection with weightings of 70 and 30% respectively [3]. A further particularity is that not months but sequences of 10 to 30 days are assembled to form an annual weather file [3].

Whilst the generation of 'typical' year weather data has been long established, with the Sandia method for example dating back to 1978 [12], the use of dedicated weather data for assessing summer overheating of naturally ventilated buildings [1,2] or building services plant performance under adverse weather conditions [3,13] is a more recent development. The need for such data that allows detailed simulation analysis under 'near-extreme' conditions and the apparent shortfalls of 'typical' weather years to deliver on this, have, since the end of the 1990s, led to some discussion. For example, in 1999 Hensen [14] proposed that reverting to real-time weather series may be the way forward for such assessments. However, as detailed in the following, to date there is no standardised method for deriving dedicated 'near-extreme' summer or winter data for building performance simulation that would be widely applied or universally accepted. Furthermore, there is no universal definition for a 'near-extreme' year, with current literature commonly relating 'near-extreme' conditions to weather as experienced in the centre year of the upper quartile of a set of years ranked according to dry bulb temperature parameters [1,2,3].

Current methods for deriving near-extreme weather data

For many locations world-wide the only information on weather extremes that is readily available to engineers are the annual design conditions tables provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [15] which contain some, albeit very limited, information on extreme annual design conditions. The need for more detailed design data for assessing building services operation under extreme temperature and humidity events has been, in the past, addressed by sequences of data which typically span several days. For example, Colliver et al [16] developed a method for producing 1, 3, 5 and 7 day sequences of hourly near-extreme weather data, which are available from ASHRAE for sites in the U.S. and Canada [17]. However, such data series are of a limited suitability to many building performance simulation applications where annual weather files are preferred.

In order to assess building overheating risk through building performance simulation, summertime weather data of selected years, typically extreme years, is often applied directly in the simulations, either using data from standard weather stations [18,19,20] or specifically measured on-site data including the local microclimatic conditions [18]. This data either encompasses a series of extreme months or represents an entire year with an extreme summer. For example, Frank [20] used multi-year weather data from 1984-2003 for Zurich-Kloten to derive a “warm reference year” by composing an annual file of the months with the highest mean dry bulb temperatures within this period. A similar approach was proposed by Ferrari and Lee [21] who suggested amalgamating the hottest summer with the coldest winter in order to form an “extreme meteorological year”. A different approach was taken in 2004 by the German National Meteorological Service (Deutscher Wetterdienst – DWD) with a set of near-extreme summer data for the months June, July, August in addition to its TRYs [13]. This data represented the summer of 1983, which was the second to fourth hottest summer within the period 1961-1995 for most German weather stations in terms of mean dry bulb temperature [13]. Similarly, near-extreme winter data was made available by the DWD for the months December, January, February, representing the winter of 1984/85 [13]. The purpose of both of these data sets was to assess building services plant operation under near-extreme conditions [13].

The UK Design Summer Years (DSYs), first published in 2002 for 3 sites [1] and amended in 2006 to incorporate more recent data and more sites [2], were the first set of standardised annual weather files representing near-extreme weather conditions that were made available for common use in the building services industry. These files were developed for determining the summer overheating performance of naturally ventilated and free running (no heating or cooling) buildings. The current UK DSYs are defined as the third hottest year in a multi-year data set based on the April to September mean dry bulb temperature [2], whilst the remaining weather parameters such as for example solar radiation, relative humidity and wind speed have no influence on the selection process. The DSYs have been, for many years, unique to the UK [2,22]. However, the need for hot summer weather years for assessing the summertime operation of naturally ventilated buildings has also been highlighted for locations outside the UK such as Germany [18,19] or the Netherlands where weather years for overheating assessment have become part of the national standard NEN 5060: 2008 [23].

In 2011 a new method for deriving extreme summer and winter years from multi-year data sets was devised for Germany by a research consortium including the DWD [3], aiming at replacing the 2004 extreme summer and winter data [13]. Similar to the UK DSYs [2] this method selects an entire year based on April to September temperature data for the extreme summer year and October to March temperature data for the extreme winter year respectively, using multi-year weather data from 1993-2007 as basis [3]. The extreme summer year is determined by ranking the years according to their April to September data, looking at the 90th percentile of the hourly dry bulb temperature and the number of days where the 95th percentile of the ‘regional’ daily maximum temperature is exceeded with weightings of 70 and 30% respectively. (Here ‘region’ corresponds to one of the 15 TRY weather regions within Germany [3,13].) The year with the second highest overall ranking is then chosen as the ‘extreme summer TRY’ which corresponds to the 90th percentile rank of the available data set [3]. For determining the ‘extreme winter TRY’ the October to March data for the winter half years is ranked according to the ‘regional’ degree days with a base temperature of 12°C and the number of days where the ‘regional’ daily maximum temperature falls below the 5th percentile, again with 70 and 30% weightings. The year with the second highest overall ranking is then chosen [3].

The advent of large amounts of computed weather data extracted from weather generators such as the UKCP09 weather generator [24], which is primarily used for climate change impact assessments, has opened up new options for deriving synthetic near-extreme weather years for building performance simulation, in particular future weather years. For example, Watkins et al [25] used the UKCP09 weather generator [24] to produce 3000 synthetic weather years which were then sorted according to monthly mean dry bulb temperature, relative humidity and global horizontal irradiance in order to produce near-extreme Design Reference Years (DRYs) for each of these parameters. The 87.5 percentile year of each data sequence with 10 years of data on either side of this year was then used in order to compose the three independent near-extreme weather years for dry bulb temperature, relative humidity and global horizontal irradiation [25], following the ISO method for weather file generation [11]. These three DRYs are intended to be used for design methods replicating the CIBSE manual design methods [25]. A different approach was taken by Du et al [26] who integrated three near-extreme months for dry bulb temperature in summer (June-August) and winter (December-February) into a TRY generated from UKCP09 weather generator outputs, looking at the 99th (summer) and 1st (winter) as well as the 85th and 15th percentile of 3000 synthetic weather years. The summer and winter months to be integrated into the two resulting weather files were selected using the Finkelstein-Schafer statistic [10] looking at a total of 30 candidate years around the given percentile year [26].

In mid-2014 a new approach for deriving near-extreme summer data was published, looking at the case of the Greater London area [27]. This selection method, which is methodically linked to the guidance on overheating in free-running buildings specified in CIBSE TM52 [28], uses a so-called ‘conceptual free running building’ which is defined as a building with an operative temperature [15,29] equal to the outdoor dry bulb temperature at any given hour [27]. Based on this assumption the comfort temperature, i.e. the operative temperature for neutral thermal comfort, can be calculated for this ‘conceptual free running building’ from the external running mean temperature following EN 15251 [30]. Whenever the outdoor dry bulb temperature (which in this case is equal to the operative temperature) exceeds the calculated comfort temperature, the temperature difference is squared and the cumulative data then forms the so-called ‘weighted cooling degree hours’ (WCDH) [27]. Based on this statistic three new DSYs were selected for London, 1989, 1976 and 2003, representing a moderately warm summer, an extended warm summer and a summer with a single extreme period respectively [27], with 1989 also representing the current London DSY [2].

Issues with current near-extreme weather data selection methods

Whilst the above highlights practical approaches for deriving near-extreme weather data for building performance simulation from multi-year data sets, the current methods are far from ideal as they are often focussed on dry bulb temperature as the sole selection criterion, disregarding other climate parameters, such as for example solar radiation. However, the solar radiation conditions are important for the overheating performance, in particular for buildings with a high fraction of glazed surface area [23]. This importance has been demonstrated by Hong et al [31] who conducted extensive building performance simulations of three office building types in two different design standards. Looking at 17 locations, they compared TMY3 simulation results with simulations using 30 years of actual weather data of the given sites. It was found that annual weather variations and in particular variations in solar radiation have a significant impact on peak electricity demand for comfort cooling [31].

As pointed out by Hensen [14], Levermore and Chow [32] as well as Watkins et al [25] high outdoor dry bulb temperatures and near-extreme solar radiation events may not coincide. This implies that near-extreme weather data selected on the basis of dry bulb temperature may range from a warm sunny year to a warm cloudy year [14,25]. Consequentially, disregarding solar radiation in the weather data selection process means that there is uncertainty with respect to the impact of the near-extreme weather data on the simulated summer overheating performance of a building. The implications of this have, for example, been demonstrated for the UK DSY data set where simulations with the Nottingham DSY deliver less overheating hours than with the TRY, whilst the Leeds DSY results in more overheating hours than expected for the given latitude, both to a large extent as a result of the solar irradiation data present in the DSY [33]. Further to this, it is also questionable whether using the most extreme climate data as undertaken in some studies [18,20,21] is useful for assessing plant failure and / or summer overheating risk of a building as this may lead to design solutions for very long return periods of 30 years or more and could potentially result in oversized plant.

In a previous study, the approach for determining the UK DSYs has been found to have significant shortcomings which can potentially lead to unreliable data series when compared to the corresponding TRYs [33]. It has been shown that [33]:

a) the difference between the DSY and TRY summer mean dry bulb temperatures as well as the average daily maximum and minimum dry bulb temperatures is not consistent across the available UK weather sites,
b) a number of sites deliver more hours above high temperature thresholds (25 and 28°C) for the TRY than the corresponding DSY,
c) the difference in mean direct horizontal irradiation between the DSYs and the corresponding TRYs is not consistent across the UK weather sites and ranges from -20% to +47% for the months June to August and -6% to +29% for April to September respectively,
d) as a consequence of points a) to c) above building performance simulations with the current data can return results for selected sites where the number of overheating hours is larger for the TRY than the DSY.

Due to the ‘holes’ in the data provided by the British Atmospheric Data Centre (BADC), a number of the DSY sites only had a limited amount of full years available for the DSY selection process at the time when the files were produced [2,33]. This is highlighted in Table 1 which shows, that for some sites, less than a third of the 22 years from 1983-2004 used for the DSY generation were available as complete years for the original DSY selection. This ‘missing data problem’ was identified as one of the key issues with the current UK DSY data set [33] which raises the question whether a more complete set of data can help to overcome some of the above shortcomings.

Since the release of the current DSYs, the data has been updated by the BADC [34]. This means that it is now possible to include several years in the selection process that were missing when the original DSYs were created. This could potentially improve the data set, even though the structural problems of the DSY selection method highlighted above would not be overcome. Furthermore, the current method of selecting the third hottest summer half-year gives different percentiles in relation to the number of years available for selection (for 20 years 18/20 = 90th percentile, for 12 years 10/12 = 83th percentile). Therefore, rather than selecting the third hottest half-year, the 90th percentile warmest year should be chosen as a fixed percentile is a more consistent approach in relation to the number of years available for the ranking.

Table 1 highlights the effect of updating the selection procedure and including now available complete years between 1983 and 2004 as well as up to 2010 for the choice of a DSY. It can be seen that for 6 of the 14 UK TRY/DSY locations – Belfast, London Heathrow, Manchester, Newcastle, Norwich and Plymouth – the additional data makes no difference to the selected year if updated 1983-

2004 data is used. Furthermore, the addition of data up to 2010 makes little difference to the selected years with only Nottingham and Plymouth displaying a change to the 1983-2004 data update.

The limited change in the selected near-extreme summer years highlighted in Table 1 is of particular relevance for the 1983-2004 update as this would be the timeframe of choice in order to be consistent with the corresponding TRYs which were derived from 1983-2004 weather data. The DSYs for Norwich and Newcastle would remain the same which would mean that the problem of these sites frequently producing fewer overheating hours in building performance simulations than the corresponding TRYs [33] would not be overcome. However, for Leeds the reduction in the hours above 25°C from 178 to 106 (Table 1) and in the hours above 28°C from 58 to 13 is likely to solve the problem of some building performance simulations delivering a comparably large number of overheating hours for the given latitude [33].

Overall, it can be concluded that updating the DSYs by including missing data does not solve the issues with the current data set as demonstrated by the case of Norwich and Newcastle. Therefore, the method of choosing the DSY based on either the third hottest year or, as done here, the 90th percentile warmest year, has to be considered as not appropriate even with a more complete data set for selecting the year. Given these shortcomings, an improved method for deriving near-extreme summer data appears to be needed which is also confirmed by the findings of CIBSE TM49 [27].

The selection procedures proposed in conjunction with weather generator outputs [25,26] are an attractive option to produce more consistent near-extreme weather data sets. However, the large amount of data that is required to be able to deliver statistically reliable information cannot be obtained with measured annual data due to the short time periods commonly available for weather file generation (typically around 20 years). Therefore, these approaches will remain confined to synthetic weather series.

The method currently used in Germany [3] is likely to be more robust than the UK DSY approach with respect to points (a) and (b) above due to the inclusion of daily maximum temperature in the data selection process. However, the solar radiation issues highlighted in point (c) above remain. Similarly, the 'weighted cooling degree hours' approach proposed in CIBSE TM49 [27] can help to overcome the high temperature threshold issue of the current DSY (see point (b) above). However, the solar radiation question also remains for this selection method. Furthermore, the dependence on a 'conceptual free running building' as a reference for the weather data selection process generates new uncertainties. This is confirmed by CIBSE TM49 which states that *"it is not possible to produce any one definition of reference building that covers all building types and further research is required to identify alternative definitions"* [27]. In addition, the selection of a single year, as with these two approaches, can result in the inclusion of exceptionally cool and warm months in the same file, which may influence the overall overheating performance of a building [33].

Summer Reference Year (SRY) method for deriving near-extreme summer weather data

The above implies that a more comprehensive approach for determining near-extreme summers is required. Based on the analysis of the current limitations in the UK DSY files it was concluded that such new data should meet the following criteria [33]:

a) *"represent a 'typical' hot summer at a given location and not an extreme summer"* [33] in order to provide design data for return periods that are within the design life of most building services systems,
b) *"have a consistent relation to the TRY in terms of dry bulb temperature and solar irradiation"* [33] in order to facilitate comparison between simulation results obtained with the two data sets and to avoid inconsistencies such as the TRY producing greater overheating for selected months than the DSY,
c) *"contain at least one warm spell period"* [33] as these are critical to building overheating [27], *"but at the same time be devoid of unrepresentative hot or cold months"* [33] that in comparison to long term data represent extreme conditions for a given site,
d) *"have a 'temperature tail' that exceeds that of the corresponding TRY for high temperatures"* [33] as the distribution of high temperatures at the cumulative 'high temperature tail' end is critical to summer overheating occurrence.

Ideally, these criteria should be met each individual month during the summer half-year in order to provide maximum consistency with the corresponding TRY. Furthermore, as the criteria are valid for locations world-wide, a solution is needed that is applicable to any location where appropriate base line weather data is available. The following presents a method for producing such files from the existing TRY of a site in conjunction with multi-year weather data, using the UK as an example.

The proposed method takes as the starting point that the TRY is robust, being determined on a monthly basis by the most typical months for the parameters of dry bulb temperature, cloud cover (for deriving global horizontal radiation) and wind speed. The resulting new files, which in essence represent artificially adjusted TRYs to meet near-extreme summer conditions, will be referred to as Summer Reference Years (SRY). The following details the methods for producing the SRY in a step by step approach for all meteorological parameters present in the original CIBSE TRY data apart from wind direction which remains unchanged.

Dry bulb temperature adjustment

The approach for generating the SRY dry bulb temperature nodes is based on a two stage process: identifying the 90th percentile warmest 'temperature tail' year from summer month (April to September) data for the TRY baseline years (typically 1983-2004) and then to mathematically adjust the existing hourly TRY data to match this candidate year for the 'high temperature tail' end following the principle of a data shift:

$$T_{dry(SRY)} = T_{dry(TRY)} + \Delta T_{dry} \qquad (1)$$

where $T_{dry(SRY)}$ and $T_{dry(TRY)}$ are the SRY/TRY dry bulb temperature and ΔT_{dry} represents the dry bulb temperature shift. The reason for such a mathematical adjustment rather than using the selected year directly is demonstrated by Figure 1 which, for the sites of London Heathrow and Manchester Ringway, shows that the monthly mean dry bulb temperature of individual years, including the respective candidate years for adjusting the TRY, varies considerably in relation to the TRY. Mathematical adjustment of the TRY can help to avoid exceptionally warm or cool months as they currently prevail in the DSYs shown in Figure 1.

Looking at the 'tails' of the temperature distribution for multi-year April to September data shown in Figure 2, one possibility for the TRY adjustment is to pick the 90th percentile warmest 'high temperature tail' year in the set. However, as the 'high temperature tails' of the individual years intersect each other, it is not instinctively clear how to determine the 90th percentile warmest. This problem becomes evident when looking at the TRY and DSY data of for example Newcastle, Norwich and Nottingham where the TRY 'tail' intersects with the DSY 'tail', highlighting that a selection procedure on the basis of mean dry bulb temperature is not a suitable approach (see also [33]). Therefore, a statistic is needed in order to select a single year. One measure that appears reasonable is to use the number of degree hours above a given base temperature as selection criterion. In this work 18°C was chosen, as this is a common base temperature for cooling degree hour assessments [29].

Table 2 shows the candidate years selected for the TRY adjustment using the number of degree hours to a base temperature of 18°C for all fourteen UK TRY/DSY locations. These years represent the 90th percentile highest year in the ranking of all available years, which for the range of the available years (16 to 23) corresponds to the 3rd year in the sequence. As can be clearly seen in Table 2 the TRYs typically rank in the median of all available years which gives confidence in their representativeness for a typical year in terms of degree hours above 18°C. Nevertheless, London and Swindon represent low outliers and Birmingham and Plymouth high outliers which does, however, only in parts reflect in the temperature distribution from the 95th percentile shown in Figure 2. Table 2 also highlights that there is no consistency in the ranking of the current DSYs. A consistent relation to the TRY should, however, be the case if the DSYs were robust.

Based on the 'high temperature tails' shown in Figure 2 for the candidate years given in Table 2 it appears reasonable to assume that using the degree hours above 18°C is a robust approach for determining a site specific near-extreme summer year in terms of the 'high temperature tail' end, yet with the potential drawback that the remainder of the year may not be very representative as demonstrated by Figure 1. To overcome this problem, that becomes particularly evident when using an individual year directly in building performance simulations, the following steps are proposed for adjusting the TRY dry bulb temperature nodes from April to September inclusive:

- Step 1: Sort the April to September daily maximum dry bulb temperature (T_{max}) for the TRY and the candidate year in descending order and work out the temperature difference between corresponding T_{max} pairs in the sequence.
- Step 2: Fit a 6th order polynomial regression through the resulting daily T_{max} temperature difference data as graphically demonstrated by Figure 3a for Glasgow Abbotsinch.
- Step 3: Work out the temperature difference between the daily minimum dry bulb temperature (T_{min}) values on the days corresponding to the daily T_{max} pairs and fit a 6th order polynomial regression through the resulting daily T_{min} temperature difference data as shown in Figure 3b for Glasgow Abbotsinch.
- Step 4: Use the regression equations calculated in steps 2 and 3 to work out the temperature shifts for the TRY daily T_{max} and T_{min} data on each day corresponding to the point in the regression sequence. For example, for the Glasgow TRY day 1 to be adjusted is the 19th of July (hottest day), day 2 the 18th of July (2nd hottest day), day 3 the 19th of June (3rd hottest day). No more data shift calculation is performed beyond the point where the daily T_{max} temperature difference regression becomes negative for the first time. Furthermore, as the T_{min} shift can potentially result in unrealistically high minima, T_{min} is capped to the maximum value of the April to September daily minimum dry bulb temperature of the TRY or the candidate year, whichever is higher.
- Step 5: Perform a linear interpolation between the shift values for T_{max} and T_{min} on the days that receive a shift. Extend the linear interpolation between T_{max} and T_{min} shift values to adjacent days where these days also receive a shift. Where the adjacent day does not receive any shift, the 12 hours adjacent to the T_{max} or T_{min} shift are used to reduce the shift to 0 through linear interpolation.

- Step 6: Calculate the SRY hourly April to September dry bulb temperature ($T_{dry(SRY)}$) profile by adding the dry bulb temperature shift values (ΔT_{dry}) determined in step 5 to the existing TRY dry bulb temperature ($T_{dry(TRY)}$) data using equation (1). The October to March data remains unchanged.

As can be seen in Figure 3a for Glasgow Abbotsinch there is a good fit between the ranked maximum dry bulb temperature difference data of the two files and the 6^{th} order polynomial regression. This is similar for other sites. However, as Figure 3b shows, there is clearly a very strong deviation in the minimum dry bulb temperature difference on the corresponding days highlighting that the night time low is not a function of the daytime high. Nevertheless, albeit weak, the 6^{th} order polynomial regression shows some trend in the data for most sites. The example of Glasgow Abbotsinch also demonstrates that the regression equation for the minimum dry bulb temperature can result in a reduction of the night time low in the SRY as compared to the TRY already prior to the point where the data shift is ceased (see step 4 above). This appears reasonable as warmer days are likely to be sunny with a clear sky resulting in higher longwave radiation losses to the sky during the night. Tables 3 and 4 show the regression coefficients for the 6^{th} order polynomial regression used for obtaining the dry bulb temperature shift (ΔT_{dry}) for adjusting the daily T_{max} and T_{min} of the 14 UK TRY weather sites following the equation:

$$\Delta T_{dry} = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6 \qquad (2)$$

where x represents the day in the adjustment sequence and a to g the regression coefficients. Table 3 also includes the last day where an adjustment is being performed and Table 4 the maximum allowable T_{min} at a given site (see step 4 above).

Figure 3c demonstrates the dry bulb temperature shift from the TRY to the SRY for Glasgow Abbotsinch looking at a one week sequence which includes the two warmest days of the year. It can be clearly seen that the SRY approach retains the temperature pattern of the TRY, at the same time producing a warm-spell period with a clear relation to the underlying TRY. Figure 3d shows that the approach is suited to replicate the temperature tail of the candidate year used for the TRY adjustment. However, it needs to be noted that for some sites (e.g. London Heathrow) this match is less perfect than for Glasgow Abbotsinch. Nevertheless, overall it can be concluded that the adjustment procedure delivers data with a clear relation to the underlying TRY whilst at the same time producing a distribution with a ‘high temperature tail’ as expected of a near extreme year (Figure 2).

Wet bulb temperature, wind speed and atmospheric pressure adjustment

Adjustment of wet bulb temperature ($T_{wet(TRY)}$), wind speed ($ws_{(TRY)}$) and atmospheric pressure ($p_{at(TRY)}$) of the TRY to produce the SRY all follow the same principle. Since the nature of the TRY as a typical weather year gives some confidence in a typical distribution of its data, the basis for adjustment is the correlation of the April to September TRY wet bulb temperature, wind speed and atmospheric pressure to the dry bulb temperature at a given site in a linear relationship:

$$y = a_y + b_y \cdot T_{dry(TRY)} \qquad (3)$$

where y represents either $T_{wet(TRY)}$, $ws_{(TRY)}$ or $p_{at(TRY)}$ and a_y and b_y the respective regression coefficients. This correlation is used in order to derive site specific dry bulb temperature correlated shift values which are then used to adjust the hourly TRY data according to the following equation:

$$z = y + b_y \cdot \Delta T_{dry} \qquad (4)$$

where z represents either $T_{wet(SRY)}$, $ws_{(SRY)}$ or $p_{at(SRY)}$. The detailed steps for the data adjustment are as follows:

- Step 1: Sort all April to September TRY wet bulb temperature / wind speed / atmospheric pressure data into dry bulb temperature bins of 0.1°C and work out the mean wet bulb temperature / wind speed / atmospheric pressure at a given dry bulb temperature as graphically demonstrated by Figure 4a for wind speed at London Heathrow.
- Step 2: Exclude all bins with less than 10 values and fit a linear regression through the remaining data as shown in Figures 4b for wind speed and Figure 5 for p_{at} and T_{wet} at London Heathrow.
- Step 3: Multiply the hourly dry bulb temperature shift values (ΔT_{dry}) determined according to the procedure detailed above with the slope of the linear regression, i.e. regression coefficient b_y of equation (3), to obtain the corresponding wet bulb temperature / wind speed / atmospheric pressure shift.
- Step 4: Calculate the SRY hourly April to September wet bulb temperature / wind speed / atmospheric pressure profile by adding the shift values determined in step 3 to the existing TRY file using equation (4).

Table 5 provides the regression coefficients b_y that were determined according to this procedure for wet bulb temperature, wind speed and atmospheric pressure. It can be seen that the adjustment for wet bulb temperature for the months of interest (April to September) is within a narrow band from 0.69 K_{wet}/K_{dry} (K = Kelvin) for Swindon to 0.84 K_{wet}/K_{dry} for Belfast. Furthermore, as demonstrated by Figure 5 for the case of London Heathrow, the correlation between wet bulb and dry bulb temperature was found to be strong, which gives some confidence in the suitability of the chosen approach for wet bulb temperature adjustment. This is confirmed by the coefficient of determination which ranges from R^2=0.97 to R^2=0.99 across all sites.

As a general tendency, an increase in wind speed was determined in relation to higher temperatures in the TRY data, yet with a low coefficient of determination (average across all sites: R^2=0.19 with a standard deviation of 0.17). This increase ranged from a marginal wind speed change for Newcastle and Plymouth to a maximum increase of 0.25 knots/K for the Edinburgh TRY, with an average increase over all sites of 0.11 knots/K (Table 5). As wind speed is provided as integer values in the TRY file format, the rather small changes per K mean that these will often be 'lost' due to rounding.

The reason for excluding data bins with less than 10 values as stated in step 2 above is highlighted by Figure 4a for the case of London Heathrow which shows that there is a trend for higher mean wind speeds at higher temperatures, yet with some scatter at the tail ends for temperature bins with a small amount of data. This finding is supported by the results for the other 13 sites. To eliminate this scatter, dry bulb temperature bins with less than 10 values were ignored which excludes on average about 10% of the data from the analysis. The implication for the gradient of the linear regression of the dry bulb temperature correlated mean wind speeds is demonstrated by Figure 4b.

For most sites a clear relation was found between dry bulb temperature and atmospheric pressure, but with scatter in the data. This also reflects in the coefficient of determination with some considerable variation between individual sites (average across all sites: R^2=0.43 with a standard deviation of 0.23).With exception of Norwich, atmospheric pressure was found to increase in relation to temperature during the summer months. However, the magnitude of the change was found to be rather small, ranging from -0.3 hPa/K for Norwich to 1.1 hPa/K for Glasgow with an average increase of 0.5 hPa/K across all sites (Table 5). This means that the adjustment will generally be small. Nevertheless, changes will be clearly visible as atmospheric pressure is given to the fist decimal in the TRY/DSY file format.

Solar irradiation adjustment

Generating the SRY solar irradiation nodes follows a similar two stage procedure as for producing the SRY dry bulb temperature: first a candidate year for the summer months (April to September) is identified from the TRY baseline years (typically 1983-2004) and then the TRY is mathematically adjusted to match the 'high direct horizontal irradiation tail' end of this candidate year. However, as it is not readily apparent how to determine a near-extreme year in terms of solar irradiation, an appropriate method for selection is required. The chosen approach is based on the components of the April to September mean daily global horizontal irradiation sum and the 95th percentile daily global horizontal irradiation sum. This considers both, the overall solar irradiation conditions and the days with the highest solar irradiation which are critical for summer overheating assessment. The exact steps for determining the candidate year for the TRY adjustment are as follows:

- <u>Step 1:</u> Sort the available baseline years according to their April to September mean daily global horizontal irradiation sum in descending order. The year with the 90th percentile ranking then becomes the 'mean irradiation candidate year'. Given the range of available years (13-23) this corresponds to the 3rd year in the sequence for all sites apart from Leeds where it corresponds to the 2nd.
- <u>Step 2:</u> For each baseline year sort the April to September data according to daily global horizontal irradiation sum in descending order. Looking at the 95th percentile of this data, i.e. the 10 sunniest days of the summer half year, determine the global horizontal irradiation sum over these days. The year with the 90th percentile ranking in the resulting sequence of years is then chosen as the '95th percentile irradiation candidate year'.
- <u>Step 3:</u> Consider the numerical values of the two candidate years as 'target values' by associating them with a factor of 1.0. Determine the fractional deviation of the remaining baseline years' data from these 'target values', subtract the deviation from 1.0 and associate the resulting fractional values with the respective years.
- <u>Step 4:</u> Multiply the two fractional values for each baseline year and determine the year with the highest overall score. This year then becomes the candidate year for the TRY adjustment.

The above method implies that the 'mean irradiation candidate year' and the '95th percentile irradiation candidate year' are equally weighted for the final selection of a candidate year for TRY adjustment. Therefore, in order to check whether this is a valid approach, the distribution of the values for both selection criteria was examined and weightings applied accordingly. However, even for Southampton which represents the site with the largest difference in weighting (0.46 to 0.54) this did not result in the selection of a different final candidate year than with an equal weighting. This was found to be due to the overall small difference in the weightings and the relatively small data sample size of 13 to 23 years. Therefore, an equal weighting appears justified.

Table 6 lists the candidate years that result for the 14 CIBSE TRY/DSY sites, also giving the number of years available for selection. Here it should be noted that due to 'holes' in the BADC data [34] there are less years available for the sites of Cardiff, Leeds, Nottingham and Plymouth than for selecting the dry bulb temperature candidate years detailed in Table 2 above. Table 6 also highlights that the selected year typically matches the target year for mean daily global horizontal irradiation sum and that the ranking according to the 95th percentile global horizontal irradiation sum is typically in the upper third of the available data, yet with Leeds, Plymouth and Swindon representing low outliers. Nevertheless, all selected years rank above the respective TRYs for both parameters.

Based on previous findings with respect to the current TRY and DSY [33] it is assumed that the difference in solar irradiation between TRY and SRY mainly affects the direct horizontal irradiation component of the global horizontal irradiation. Based on this assumption the following steps are then proposed for adjusting the global horizontal irradiation nodes of the TRY from April to September inclusive:

- Step 1: Calculate the direct horizontal irradiation (I_{dirhor}) by subtracting the diffuse horizontal irradiation (I_{difhor}) from the global horizontal irradiation (I_{glhor}) for each April to September hourly time step in the original TRY data and the candidate year.
- Step 2: Calculate the daily totals for direct horizontal irradiation (ΣI_{dirhor}) for each day from April to September for the TRY and the candidate year, sort the resulting data in descending order and work out the direct horizontal irradiation difference between corresponding pairs.
- Step 3: Fit a 6th order polynomial regression through the resulting daily direct horizontal irradiation difference data as shown in Figure 6 for Glasgow Abbotsinch.
- Step 4: Use the regression according to equation (4) to work out the daily direct horizontal irradiation shift for the TRY data on each day corresponding to the point in the regression sequence. For example, for the Glasgow TRY day 1 to be shifted is the 2nd of June (sunniest day), day 2 the 29th of May (2nd sunniest day), day 3 the 17th of July (3rd sunniest day). No more data shift calculation is performed beyond the point where the regression becomes negative for the first time, excluding the first 3 data points, where negative values are ignored. (The occurrence of such negative values in the regression is related to the fact that the difference between the irradiation of the TRY and the candidate year tends to be small for the first few nodes, whilst it is considerably larger for the subsequent data as illustrated by Figure 6. Therefore, the impact of ignoring these values was found to be small.) Furthermore, in order to avoid unrealistically high solar irradiation data, the direct horizontal irradiation shift is capped so that the direct horizontal irradiation sum (ΣI_{dirhor}) on any day does not exceed the maximum value for the TRY or the candidate year, whichever is higher.
- Step 5: Scale the hourly direct horizontal irradiation by multiplying it with the hourly value for cloud cover (in octa), using a factor of 1 where the cloud cover equals 0. Calculate the share of each hour of the scaled daily direct horizontal irradiation on days that require adjustment in the TRY and scale the total daily direct horizontal irradiation shift with this hourly share in order to receive the respective hourly shift values. This method gives hours with a larger cloud cover a larger share in the adjustment which appears reasonable as an overall sunnier day is being created.
- Step 6: Add the shift values to the hourly April to September global horizontal irradiation profile of the existing TRY file to obtain the SRY.
- Step 7: Calculate the hourly clear sky global horizontal irradiation (I_{GC}) using the clear sky model by Perrin de Brichambaut and Vauge as discussed by Rigollier et al. [35] and assess whether the adjusted hourly global horizontal irradiation (I_{glhor}) is smaller than this value. Adjust any global horizontal irradiation data that exceeds the clear sky global irradiation (I_{GC}) to match this maximum value.

Table 7 provides the coefficients for the 6th order polynomial regression used for adjusting the daily direct horizontal irradiation of the 14 UK TRY weather sites. It also includes the last day with an adjustment for each site and the maximum allowable value for daily direct horizontal irradiation.

The change in global horizontal irradiation as detailed above also has implications for the diffuse irradiation fraction since the hourly clearness index KT_h is affected by this alteration. Therefore, the diffuse irradiation needs to be recalculated in order to reflect this change. The Boland-Ridley-Lauret (BRL) model [36] is used for this purpose as this model was found to perform better than other common models for deriving diffuse irradiation [36,37] and is also utilized in the current version of the widely applied weather database calculation tool Meteonorm [38].

Cloud cover adjustment

Following the change in global horizontal irradiation the cloud cover data may no longer be consistent with the solar irradiation data. Therefore the SRY April to September daytime cloud cover is recalculated on the basis of the work of Gul et al. [39] which in essence represents a refinement of the empirical radiation model on the basis of cloud cover by Kasten and Czeplak [40] with UK site specific coefficients. This model requires the clear sky global horizontal radiation (I_{Gc}) as an input. It needs to be noted that, due to the empirical nature of the model, the more accurate I_{Gc} of the model by Perrin de Brichambaut and Vauge discussed above [35] cannot be used for this purpose and I_{Gc} needs to be recalculated according to the following equation:

$$I_{Gc(CRM)} = A\, sin\gamma_s - B \qquad (5)$$

where A and B are local coefficients derived by Gul et. al. [39] and γ_s represents the solar altitude angle which can be calculated according to the procedures given in CIBSE Guide J [1]. In order to obtain cloud cover N (in octas) equation (12) in Gul et. al. [39] becomes:

$$N = 8 \cdot \left(\frac{1}{C} \cdot \left(1 - \frac{I_{glhor}}{I_{Gc}}\right)\right)^{\frac{1}{D}} \qquad (6)$$

where C and D are local coefficients. As there is only a limited number of sites available with local coefficients for the UK [39,41] the coefficients of the locations closest to the 14 TRY sites were chosen for the calculation. These are given in Table 8. However, as Gul et al. [39] note, even the coefficients originally used by Kasten and Czeplak [40] for Hamburg can be used for UK sites. Therefore, using the closest available UK data appears reasonable. Nevertheless, whilst the locally adjusted Kasten and Czeplak [40] cloud cover radiation model (CRM) was found to perform effectively for warm temperate climates [39] and was identified to deliver better results in comparison with other cloud cover based radiation models [42], its applicability to other than temperate climate regions was however found to be limited [38]. Therefore, whilst the approach presented here appears reasonable for the UK, for other sites a detailed calculation of the clear sky global as well as diffuse horizontal irradiation following, for example, the procedures proposed by Rigollier et al. [35] will be required. From this the cloud cover can then be calculated according to the method proposed in the Meteonorm handbook [38] by applying the relative nebulosity index developed by Perraudeau [43].

Building performance simulation results obtained with the SRY

In order to test the performance of the SRY data and to determine the robustness of the overall approach CIBSE TM33 [44] overheating test G8.3 was run with the TRY, DSY and the SRY data for all 14 CIBSE TRY/DSY sites. This test uses a simulation model of a free running building with a defined light weight construction and glazing type [44]. It needs to be noted that the CIBSE TM33 test G8 simulation model as shown in Figure 7 is not a model of a realistic building but a standardised model for software evaluation, the advantage however being that it produces overheating estimates within a defined tolerance area for a range of simulation software products that have been tested with it.

TRNSYS [45] was used for the simulations presented here. In a first step the simulation was run with the CIBSE TM33 DSY in order to verify the simulation model. It was found that the simulation results for operative temperature fall within the acceptable tolerance band provided for test G8.3 in CIBSE TM33 [44]. The TRNSYS simulation model used in this study can therefore be considered as robust. As can be seen in Figure 8 a clear relation exists between the simulation results for the SRY and TRY for all sites in that the SRY never fails to produce more hours above a given operative temperature than the corresponding TRY and that the resulting curves are mostly parallel. Conversely, the curves resulting from the simulations with the DSY do not show a clear relation to the TRY, in some cases even lying below (Nottingham), intersecting (Norwich) or roughly equalling (Swindon) the TRY for operative temperatures above 25°C.

Figure 8 also highlights that for 9 of the 14 sites (Belfast, Cardiff, Edinburgh, Glasgow, Manchester, Norwich, Nottingham, Southampton and Swindon) the SRY delivers more high temperature hours at the very tail end than the DSY which is critical for overheating assessment. This demonstrates the importance of using a selection matrix that gives more weight to the high dry bulb temperature end and includes solar radiation. However, for Birmingham the SRY and DSY produce a roughly equal high operative temperature tail for CIBSE TM33 overheating test G8.3. This may, to some extent, be due to the fact that the candidate year for scaling solar irradiation (1989) is identical to the current DSY. Conversely, for Leeds and London frequently a smaller number of high temperature hours are observed. For Leeds this helps to overcome the previous shortfall of the DSY producing too many overheating hours in simulations [33]. For London the deviation also appears reasonable given that the original DSY for London (1989) was the sunniest year regarding the 95th percentile daily global horizontal irradiation sum and the 2nd in terms of mean global horizontal irradiation, whilst for all other sites the current DSY ranks lower than the SRY candidate year for the solar irradiation adjustment. This is also a further indication that the SRY selection method appears to be delivering a more consistent data set across all sites. However, it needs to be noted that the London data represents Heathrow Airport which is located in a suburban area and, henceforth, does not reflect the urban heat island over the city centre as demonstrated by the data presented by Jones and Lister [46]. As a result, albeit methodically more consistent, the reduction in the hot temperature tail of the SRY in comparison to the DSY appears counterintuitive for building performance simulations looking at the city centre. Therefore, the pDSYs for London Weather Centre discussed in CIBSE TM49 [27] should be used for central London locations.

For Plymouth and Newcastle Figure 8 shows operative temperatures of the DSY exceeding the SRY at the very ‘tail’ end. Unlike London, this cannot be readily explained from the sequence of the raw-data years. For Plymouth the reason for this may be that the original DSY has explicitly high dry bulb temperatures at the very ‘tail’ end as can be seen in Figure 2. However, for Newcastle the reasons are not readily apparent. Nevertheless, overall it can be concluded from the simulations with CIBSE TM33 [44] that the SRY approach appears to deliver better on assessing building overheating than the current DSY by providing a greater consistency to the TRY. However, for conclusive evidence further assessments are required looking at a range of buildings and evaluating the data’s robustness in comparison to multi-year simulations.

Conclusions and outlook

This paper has addressed the need for a more robust approach to generating near-extreme summer year weather data. The resulting Summer Reference Year (SRY) method for adjusting current TRYs with data from near-extreme candidate years has been found to have a number of distinct advantages over using such candidate year weather data series directly in simulations. These are as follows:

- The approach ensures that both, near-extreme dry bulb temperature and solar irradiation conditions are considered for the SRY generation. This allows for the relevance of these two parameters for building overheating. At the same time the independent scaling of the two parameters prevents the accidental use of extreme conditions. This can happen if the selection procedure is based on dry bulb temperature only and the remaining climate data is merely transferred from the temperature candidate year. This is, for example, the case with the current London DSY which represents an extreme summer year in terms of solar irradiation.
- The method results in realistic high ‘temperature tails’ that sit well within multi-year data sets for a given site and exceed those of the underlying TRYs. By contrast, particularities for dry bulb temperature and solar irradiation that may be present in the candidate years underlying the SRY, e.g. an exceptionally warm month following an exceptionally cool month, are not transferred to the SRY.
- The SRY has a consistent relation to the underlying TRY file across all climate parameters which facilitates comparison of simulation results.
- Once the regression equations for dry bulb temperature and direct horizontal irradiation as well as the adjustment factors for wet bulb temperature, wind speed and atmospheric pressure have been worked out, the SRY data can be computed directly from the TRY without the need for any additional weather data. It would, therefore, be possible to generate a TRY/SRY conversion tool rather than distributing the SRY files directly. This can help to overcome potential licensing issues with the underlying multi-year weather data.
- Unlike the CIBSE TM49 [27] approach for the pDSYs, the proposed SRY method is not dependent on a reference ‘conceptual free running building’.
- Provided that sufficient multi-year data is available for working out the regression equations, the approach can be used for sites world-wide and is not confined to the UK reference discussed here.

The above demonstrates that the SRY files in essence take the most robust components of both the TRY and the candidate years for near-extreme summer data, i.e. the underlying site-typical weather profile of the TRY and the high temperature and direct solar irradiation ‘tail’ ends of the candidate years. As a consequence the SRY method appears to effectively overcome the shortfalls of existing selection approaches such as the DSY. It addresses three of the four criteria for a more robust near-extreme summer year detailed further above. Yet, it remains uncertain whether a warm spell period is routinely captured within the new data. This will require further detailed assessment of the SRY time series in comparison to multi-year weather data. Further uncertainties exist as per the matching of high dry bulb temperatures and sunny days which may not be consistent between the data sets. For example, the warmest days during April to September in the TRY may not equal the sunniest days, whilst in the SRY candidate years this may well be the case. This issue is highlighted by Figure 9a for Glasgow Abbotsinch which shows that the 10 warmest days of the TRY do not simultaneously represent the 10 sunniest days. However, 5 of the 10 sunniest days do occur in the sequence of the 10 warmest days. Contrary to the TRY and consequentially the SRY shown in Figure 9a the three warmest days of the temperature and solar irradiation candidate years displayed in Figure 9b include daily global horizontal irradiation data close to the maximum values. This difference will have an impact on building performance simulations with the respective files. However, Figure 9b also shows a considerable overall variation in solar irradiation for the 10 warmest days of the two candidate years similar to that displayed in Figure 9a. This serves to highlight that warm days are not necessarily a function of sunny conditions which also concurs with previous work [25,31].

Overall, further investigations appear to be required, looking at a number of sites in order to determine whether there is any risk of creating unreliable data sets for the high 'temperature tail' end critical to building overheating. Nevertheless, it can already be concluded that the SRY method appears to have the potential for replacing current approaches for selecting near-extreme summer data for sites globally. Initial building performance simulations using CIBSE TM33 overheating test G8.3 [44] for the 14 UK CIBSE TRY weather sites appear to confirm this by showing promising overheating results for the SRY in relation to the underlying TRY and the current DSY. However, further work is required, investigating the robustness of the SRY method and validating the resulting climate data. This will need to include detailed meteorological testing of the resulting weather series in their plausibility for a given site as well as extensive building performance simulation studies for various building types and configurations. This should also encompass a comparison of TRY and SRY building performance simulation outputs for a number of sites in the UK and further countries.

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Table 1. Comparison of the number of years available for data selection, the finally selected near-extreme summer year and the number of hours above 25°C for the original UK Design Summer Year (DSY) files and DSYs with updated data from 1983-2004 / 1983-2010 that were selected on the basis of the 90th percentile year in the ranking according to mean summer dry bulb temperature (Data sets where the updated DSY represents the same year as the current DSY are shown in bold).

Location	Original DSY (1983-2004)*, 3rd warmest summer			Updated DSY (1983 - 2004)*, 90th percentile warmest summer			Updated DSY (1983-2010)*, 90th percentile warmest summer		
	Number of years	Year	Hours > 25°C	Number of years	Year	Hours > 25°C	Number of years	Year	Hours > 25°C
Belfast	**15**	**1999**	**8**	**23**	**1999**	**8**	**28**	**1999**	**8**
Birmingham	7	1989	109	22	1998	64	28	1998	64
Cardiff	14	1999	18	23	1998	7	28	1998	7
Edinburgh	21	1997	10	22	1999	8	22	1999	8
Glasgow	21	1997	11	21	1984	35	21	1984	35
Leeds	11	1995	178	16	1989	106	16	1989	106
London	**15**	**1989**	**267**	**23**	**1989**	**267**	**28**	**1989**	**267**
Manchester	**11**	**1999**	**52**	**22**	**1999**	**52**	**22**	**1999**	**52**
Newcastle	**12**	**1999**	**6**	**19**	**1999**	**6**	**23**	**1999**	**6**
Norwich	**10**	**2004**	**35**	**23**	**2004**	**35**	**23**	**2004**	**35**
Nottingham	7	2002	25	21	1999	68	27	2004	33
Plymouth	**9**	**1990**	**36**	**21**	**1990**	**19**	27	1995	87
Southampton	6	1982	26	22	1995	228	22	1995	228
Swindon	6	1999	66	21	1997	55	27	1997	55

* Some of the original TRY/DSY files include data up to 2005. Consequentially the number of years available for selection may be 23 for selected sites. Edinburgh, Glasgow and Southampton include data from 1978 onwards as no more data is available after 1999, 1998 and 2000 respectively.

Table 2. Candidate years for dry bulb temperature adjustment according to the degree hours above 18°C selection criterion and their ranking in relation to the number of years available. The rankings for the TRYs and DSYs are also given. TRY: Test Reference Year; DSY: Design Summer Year.

Location	Candidate year for dry bulb temperature adjustment	Number of years available for selection	Ranking according to degree hours to the base of 18°C*		
			candidate year	TRY	DSY
Belfast	1989	23	3	13	9
Birmingham	2003	22	3	9	5
Cardiff	1990	23	3	12	7
Edinburgh	1983	22	3	10	4
Glasgow	1983	21	3	11	6
Leeds	1989	16	3	8	1
London	1990	23	3	14	5
Manchester	2003	22	3	10	7
Newcastle	1997	19	3	11	6
Norwich	1997	23	3	11	13
Nottingham	1983	21	3	11	15
Plymouth	2003	21	3	8	5
Southampton	1989	22	3	11	15
Swindon (Boscombe Down)	2003	21	3	13	7

* The TRY is not counted in the ranking where the DSY rank exceeds that of the TRY in the sequence.

Table 3. Regression coefficients for shifting the TRY daily maximum dry bulb temperature.

Location	Regression coefficient							Last day with an adjustment
	a	b	c	d	e	f	g	
Belfast	3.65E+00	-3.08E-02	-2.63E-03	7.53E-05	-8.22E-07	4.04E-09	-7.44E-12	123
Birmingham	2.57E+00	-1.52E-01	7.21E-03	-1.29E-04	1.02E-06	-3.66E-09	4.84E-12	183
Cardiff	4.30E+00	-2.03E-01	6.53E-03	-1.16E-04	1.04E-06	-4.36E-09	6.79E-12	166
Edinburgh	9.85E-01	-3.35E-04	6.81E-04	-4.28E-05	6.25E-07	-3.64E-09	7.57E-12	55
Glasgow	4.71E+00	-2.48E-01	8.22E-03	-1.48E-04	1.29E-06	-5.31E-09	8.35E-12	70
Leeds	1.80E+00	-4.39E-02	2.19E-03	-3.99E-05	3.33E-07	-1.35E-09	2.08E-12	145
London	3.59E+00	-1.71E-01	7.48E-03	-1.70E-04	1.86E-06	-9.45E-09	1.79E-11	183
Manchester	9.24E-01	2.18E-02	1.20E-03	-4.04E-05	4.52E-07	-2.29E-09	4.50E-12	183
Newcastle	-2.61E-01	2.37E-01	-1.18E-02	2.58E-04	-2.71E-06	1.33E-08	-2.43E-11	123
Norwich	2.18E-01	1.16E-01	-4.98E-03	8.39E-05	-6.96E-07	2.88E-09	-4.78E-12	170
Nottingham	2.24E+00	-5.63E-02	5.03E-03	-1.51E-04	1.79E-06	-9.35E-09	1.80E-11	80
Plymouth	2.69E+00	-1.61E-02	-3.06E-04	1.68E-05	-2.15E-07	1.05E-09	-1.79E-12	152
Southampton	1.05E+00	1.10E-01	-2.08E-03	6.37E-06	1.63E-07	-1.56E-09	3.83E-12	153
Swindon	4.85E+00	-2.92E-01	9.15E-03	-1.41E-04	1.19E-06	-5.30E-09	9.71E-12	183

Table 4. Regression coefficients for shifting the TRY daily minimum dry bulb temperature.

Location	Regression coefficient a	b	c	d	e	f	g	Maximum for T_{min}
Belfast	1.22E+00	-4.84E-02	1.13E-03	-2.69E-05	3.71E-07	-2.40E-09	5.63E-12	17.0
Birmingham	-3.08E+00	6.57E-01	-3.43E-02	7.62E-04	-8.01E-06	3.95E-08	-7.35E-11	17.9
Cardiff	3.35E+00	-2.09E-01	6.47E-03	-1.16E-04	1.04E-06	-4.25E-09	6.10E-12	17.9
Edinburgh	1.32E+00	-3.26E-02	1.23E-03	-2.79E-05	2.79E-07	-1.24E-09	1.97E-12	16.2
Glasgow	2.49E+00	9.53E-02	-3.12E-03	-1.29E-05	7.21E-07	-5.35E-09	1.21E-11	15.4
Leeds	2.03E+00	-4.01E-01	1.77E-02	-3.13E-04	2.70E-06	-1.15E-08	1.95E-11	19.2
London	3.92E-01	1.44E-02	7.18E-04	-7.23E-05	1.17E-06	-6.80E-09	1.33E-11	19.9
Manchester	-5.70E-01	2.00E-01	-9.29E-03	2.01E-04	-2.16E-06	1.10E-08	-2.12E-11	20.5
Newcastle	9.58E-01	9.86E-02	-5.54E-03	1.14E-04	-1.17E-06	5.83E-09	-1.09E-11	18.2
Norwich	1.69E+00	1.23E-01	-7.69E-03	1.51E-04	-1.36E-06	5.76E-09	-9.32E-12	18.1
Nottingham	5.84E-01	-1.85E-01	1.13E-02	-2.66E-04	2.88E-06	-1.45E-08	2.76E-11	17.9
Plymouth	2.27E+00	-1.44E-01	6.12E-03	-1.16E-04	1.13E-06	-5.53E-09	1.06E-11	18.5
Southampton	3.69E+00	-2.63E-01	7.33E-03	-6.96E-05	1.61E-07	7.65E-10	-3.04E-12	20.5
Swindon	6.03E+00	-4.88E-01	1.33E-02	-1.44E-04	5.95E-07	-1.56E-10	-3.01E-12	19.4

Table 5. Shift values per K dry bulb temperature change for adjusting the TRY wet bulb temperature / wind speed / atmospheric pressure in order to obtain the corresponding SRY data. TRY: Test Reference Year, SRY: Summer Reference Year.

Location	Adjustment per K dry bulb temperature change		
	Wet bulb temperature (K_{wet}/K_{dry})	Wind speed (knots/K_{dry})	Atmospheric pressure (hPa/K_{dry})
Belfast	0.84	0.09	0.91
Birmingham	0.77	0.05	0.43
Cardiff	0.77	0.09	0.20
Edinburgh	0.81	0.25	0.61
Glasgow	0.82	0.18	1.08
Leeds	0.75	0.14	0.09
London	0.74	0.17	0.20
Manchester	0.77	0.10	0.70
Newcastle	0.79	0.02	0.97
Norwich	0.78	0.22	-0.28
Nottingham	0.76	0.05	0.65
Plymouth	0.81	0.03	0.33
Southampton	0.77	0.07	0.26
Swindon	0.69	0.08	0.67

Table 6. Candidate years for solar irradiation adjustment selected on the basis of the April to September mean daily global horizontal irradiation and 95th percentile daily global horizontal irradiation sum and ranking of these years in relation the number of years available for selection.

Location	Candidate year for solar irradiation adjustment	Number of years available for selection	Ranking of candidate year according to:	
			mean daily global horizontal irradiation	95th percentile global horizontal irradiation sum
Belfast	1989	23	5	2
Birmingham	1989	22	3	2
Cardiff	1989	21	3	2
Edinburgh	1984	22	3	3
Glasgow	1989	21	3	1
Leeds	1995	13	2	5
London	1984	23	3	3
Manchester	1984	22	3	6
Newcastle	1994	18	3	5
Norwich	1995	23	3	5
Nottingham	1989	20	2	2
Plymouth	1989	20	3	7
Southampton	1984	22	3	2
Swindon (Boscombe Down)	1990	21	3	9

Table 7. Regression coefficients for shifting the TRY daily direct horizontal radiation component.

Location	Regression coefficient a	b	c	d	e	f	g	Last day with an adjustment	Maximum for daily ΣI_{dirhor}
Belfast	6.08E+01	1.61E+01	-9.14E-02	-5.75E-03	9.64E-05	-5.72E-07	1.19E-09	128	5042
Birmingham	3.48E+02	3.57E+01	-1.46E+00	2.48E-02	-2.17E-04	9.45E-07	-1.62E-09	179	5086
Cardiff	3.59E+02	3.64E+01	-2.02E+00	3.75E-02	-3.20E-04	1.29E-06	-1.97E-09	183	5189
Edinburgh	2.96E+02	1.10E+02	-5.13E+00	9.84E-02	-9.27E-04	4.21E-06	-7.34E-09	133	4934
Glasgow	2.79E+01	4.92E+01	-1.96E+00	3.05E-02	-2.31E-04	8.52E-07	-1.22E-09	137	4996
Leeds	2.40E+02	8.64E+01	-4.40E+00	8.61E-02	-8.02E-04	3.56E-06	-6.06E-09	181	5081
London	1.12E+02	4.52E+01	-7.66E-01	-1.97E-03	1.08E-04	-7.15E-07	1.46E-09	168	4994
Manchester*	-3.61E+02	1.06E+02	-2.96E+00	3.34E-02	-1.77E-04	4.10E-07	-2.63E-10	183	4926
Newcastle	2.68E+02	-1.29E+01	8.82E-01	-1.74E-02	1.39E-04	-4.73E-07	5.46E-10	119	5090
Norwich	1.28E+02	2.53E+01	-1.64E+00	3.78E-02	-3.85E-04	1.78E-06	-3.08E-09	177	5074
Nottingham*	-1.82E+02	7.90E+01	-2.96E+00	4.54E-02	-3.42E-04	1.25E-06	-1.79E-09	151	5068
Plymouth*	-6.29E+01	3.13E+01	-1.21E+00	2.33E-02	-2.21E-04	1.00E-06	-1.74E-09	179	5244
Southampton*	-1.20E+02	6.03E+01	-1.31E+00	8.67E-03	1.68E-05	-3.80E-07	1.04E-09	166	5152
Swindon*	-2.77E+02	1.24E+02	-5.05E+00	9.01E-02	-7.99E-04	3.43E-06	-5.71E-09	181	5028

* For Nottingham, Plymouth, Southampton and Swindon the first two nodes need to be excluded from the adjustment and for Manchester the first three nodes in order to avoid a reduction (see Step 4 in the description of the global horizontal irradiation adjustment).

Table 8. Local coefficients of the cloud cover radiation model (CRM) by Gul et al. [39] used for the 14 UK TRY weather sites.

Location	Met Office weather station	Latitude/ longitude [°]	Closest station with CRM coefficient [39]	Latitude/ longitude [°]	CRM coefficients from Gul et al. [39]			
					A	B	C	D
Cardiff	St. Athan	51.41/-3.34	Aberporth	52.14/-4.57	1024	54	0.71	4.2
Plymouth	Mountbatten	50.35/-4.12						
Belfast	Aldergrove	54.66/-6.22	Aldergrove	54.66/-6.22	956	34	0.70	3.1
Edinburgh	Turnhouse	55.95/-3.35						
Glasgow	Abbotsinch	55.87/-4.43						
Birmingham	Coleshill	52.48/-1.74	Finningley	53.48/-1.01	902	36	0.71	3.7
Leeds	Leeds w.c.	53.80/-1.56						
Manchester	Ringway	53.36/-2.28						
Newcastle	Newcastle w.c.	54.98/-1.60						
Nottingham	Watnall	53.01/-1.25						
London	Heathrow	51.48/-0.45	London	51.51/-0.12	948	49	0.71	3.4
Norwich	Coltishall	52.76/1.36						
Southampton	Southampton w.c.	50.90/-1.41						
Swindon	Boscombe Down	51.16/-1.75						

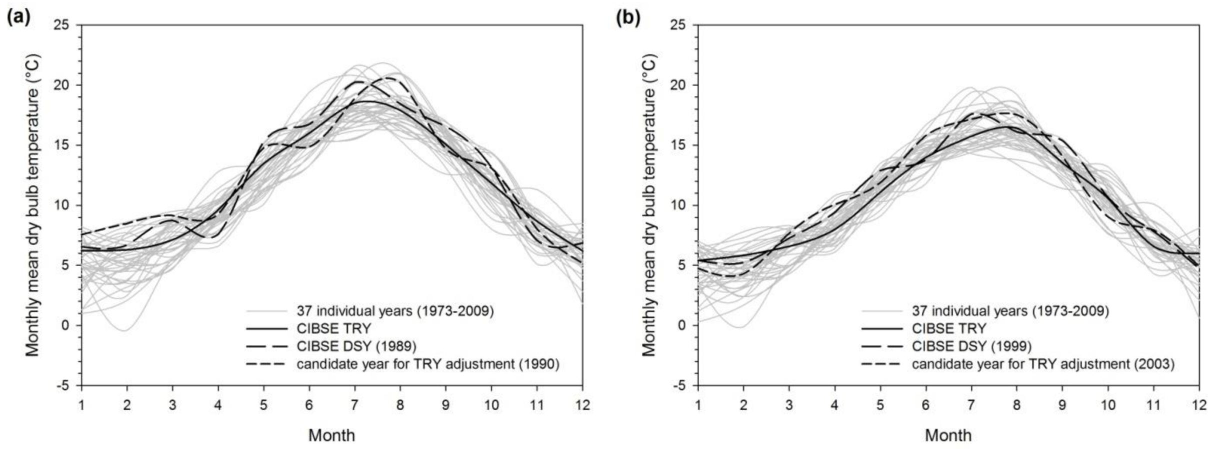

Figure 1. Monthly mean dry bulb temperatures for (a) London Heathrow and (b) Manchester Ringway, comparing the TRY, DSY and the candidate year used for adjusting the existing TRY with 37 individual years from 1973 to 2009. TRY: Test Reference Year; DSY: Design Summer Year.

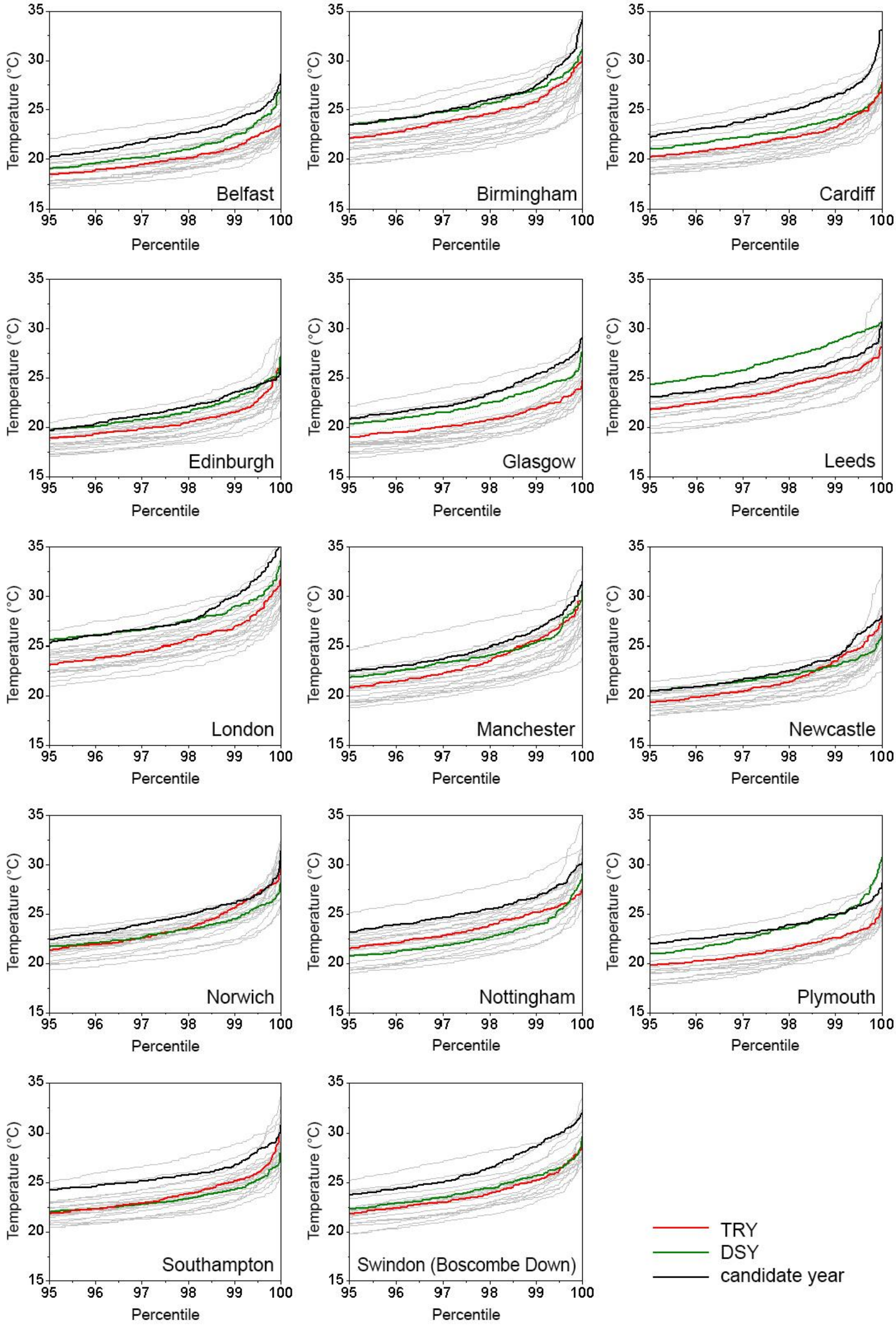

Figure 2. Ordered summer month (April-September) dry bulb temperature data from the 95th percentile for the years 1984-2010 for all UK TRY/DSY locations, also highlighting the positions of the TRY, the current DSY and the candidate year for dry-bulb temperature adjustment.

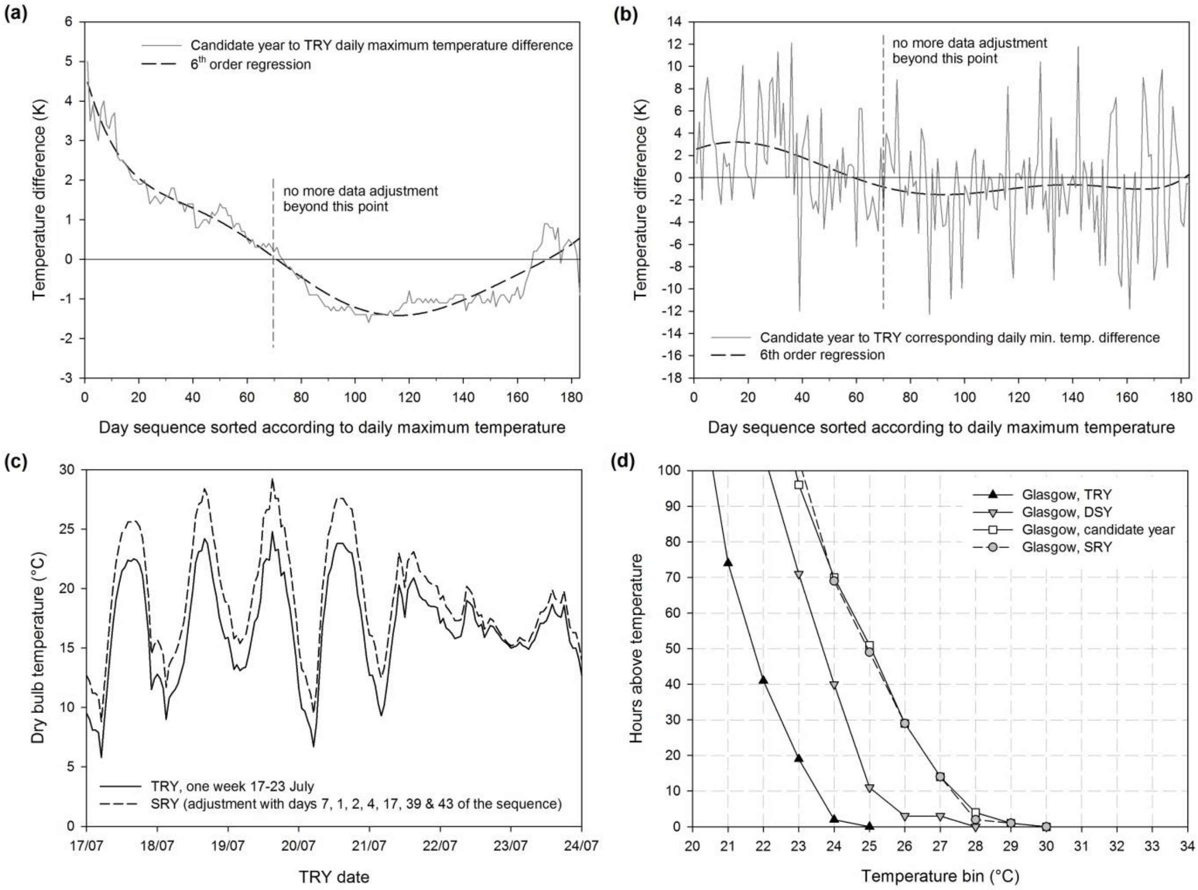

Figure 3. Glasgow Abbotsinch dry bulb temperature adjustment from the TRY to the SRY: (a) difference in daily maximum temperature between the candidate year and the TRY sorted in descending order for all days from April to September, (b) difference in daily minimum temperature between the candidate year and the TRY on the days corresponding to the T_{max} data pairs, (c) one week sequence of SRY dry bulb temperature data in relation to the underlying TRY, (d) hours above the given dry bulb temperature for the TRY, DSY, candidate year and the SRY. TRY: Test Reference Year; DSY: Design Summer Year; SRY: Summer Reference Year.

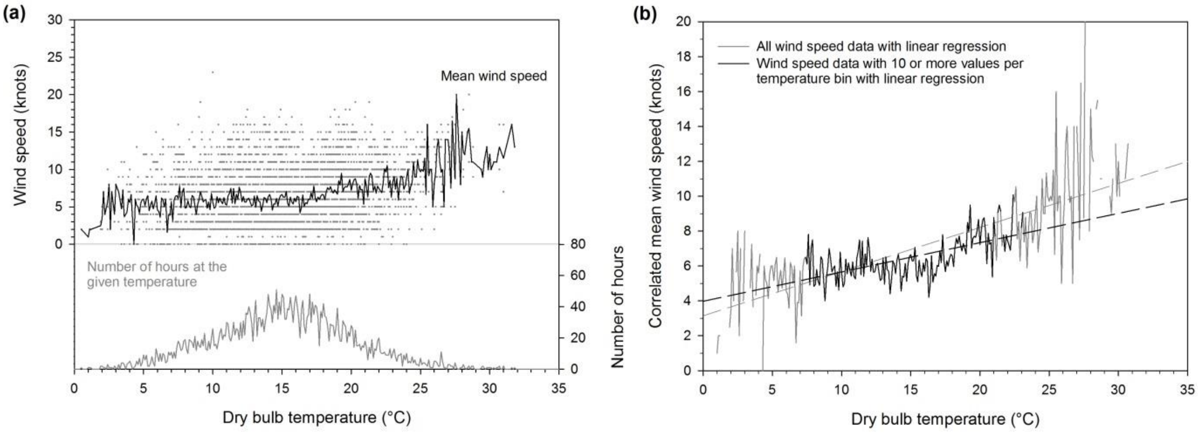

Figure 4. London Heathrow April to September TRY hourly wind speed data sorted into 0.1°C dry bulb temperature bins: (a) binned data, mean wind speed and the number of hours at the given dry bulb temperature, (b) implication of excluding wind speed data with less than 10 values per temperature bin for the linear regression.

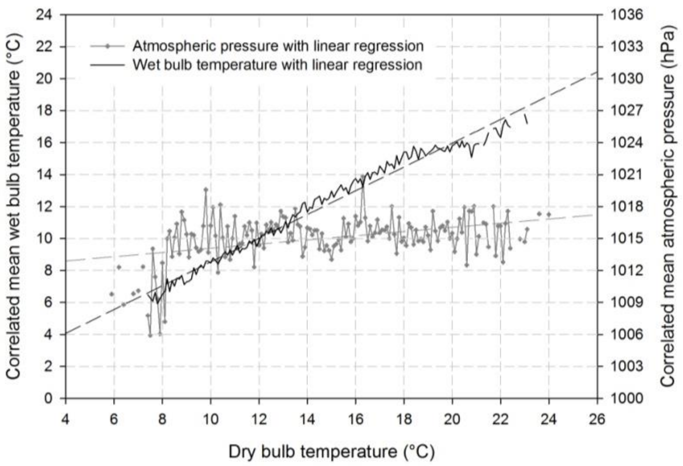

Figure 5. London Heathrow April to September mean wet bulb temperature and mean atmospheric pressure in relation to dry bulb temperature bins of 0.1°C including linear regressions. (Data with less than 10 values per temperature bin is excluded from the analysis.)

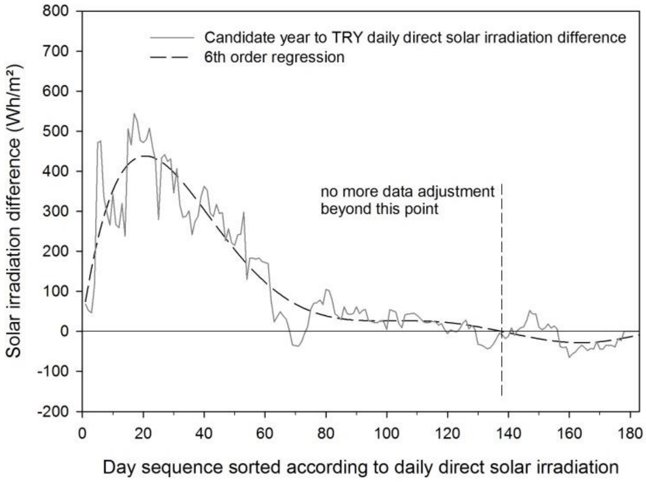

Figure 6. Glasgow Abbotsinch, difference between the candidate year and TRY daily direct horizontal irradiation data sorted in descending order.

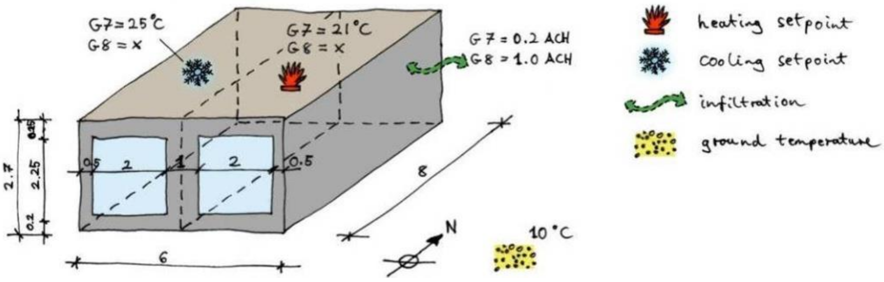

Figure 7. CIBSE TM33 [44] simulation model for tests G7 (Annual cooling and heating demand) and G8 (Overheating risk), including cooling / heating setpoint and air infiltration levels

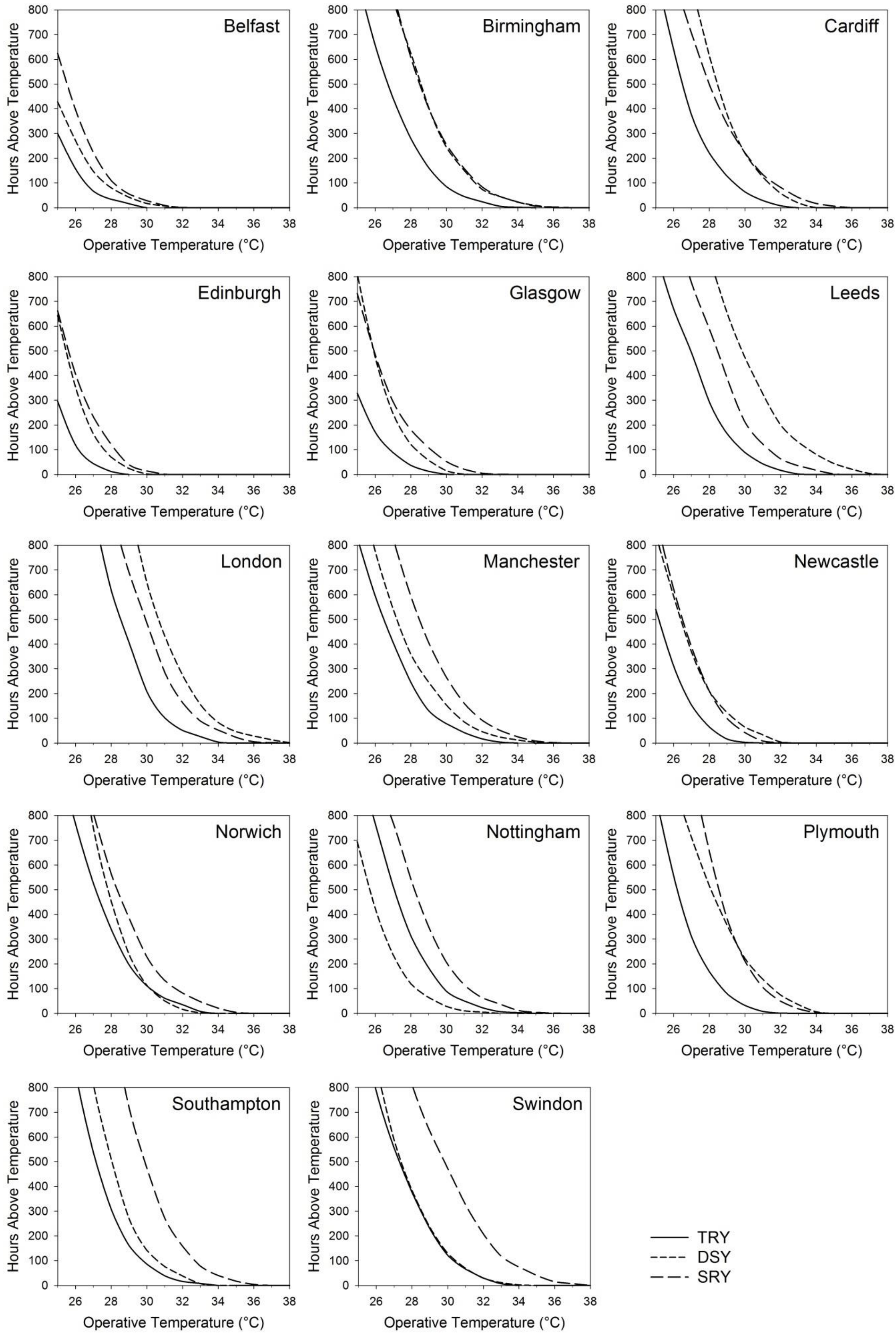

Figure 8. CIBSE TM33 G8.3 test results using TRY, DSY and SRY data for all UK TRY/DSY locations. TRY: Test Reference Year; DSY: Design Summer Year; SRY: Summer Reference Year.

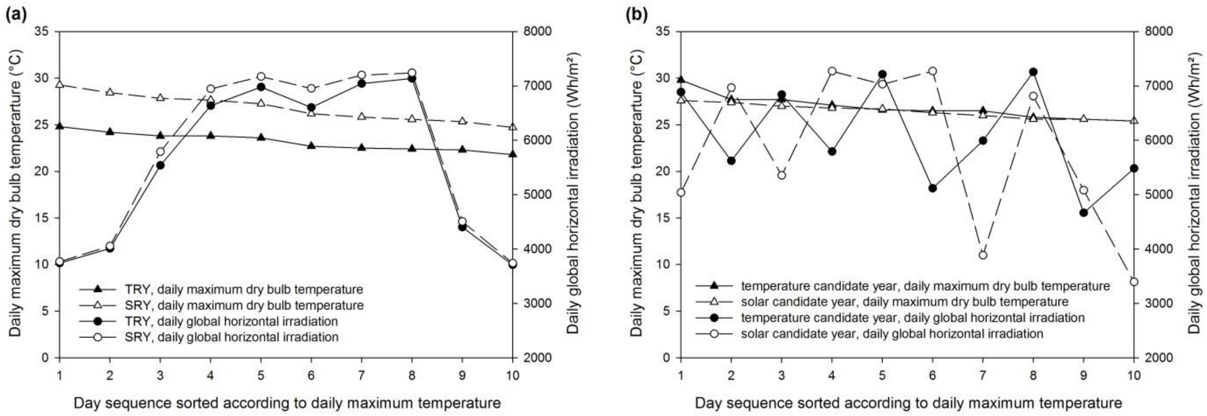

Figure 9. Glasgow Abbotsinch, daily maximum dry bulb temperature and daily global horizontal irradiation on the warmest 10 days sorted in descending order according to daily maximum temperature for (a) the TRY and the SRY and (b) the candidate years for dry bulb temperature and solar irradiation adjustment.