

# **On the creation of future probabilistic design weather years from UKCP09**

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Weather data are used extensively by building scientists and engineers to study the performance of their designs, help compare design alternatives and ensure compliance with building regulations. Given a changing climate, there is a need to provide data for future years so that practising engineers can investigate the impact of climate change on particular designs and examine any risk the commissioning client might be exposed to. In addition, such files are of use to building scientists in developing generic solutions to problems such as elevated internal temperatures and poor thermal comfort. With the publication of the UK Climate Projections (UKCP09) such data can be created for future years up to 2080 and for various probabilistic projections of climate change by the use of a weather generator. Here we discuss a method for the creation future probabilistic reference years for use within thermal models. In addition, a comparison is made with the current

set of future weather years based on the UKCIP02 projections. When used within a dynamic thermal simulation of a building the internal environments created by the current set of future weather files lie within the range of the internal environments created by the probabilistic reference years generated by the weather generator. Hence the main advantages of the weather generator are seen to lie in its potentially greater spatial resolution, its ability to inform risk analysis and that such files, unlike ones based on observed data, carry no copyright.

### **Practical Implications**

The methodology presented in this paper will allow academics and buildings engineers to create realistic hourly future weather files using the future climate data of UKCP09 weather generator. This will allow the creation of consistent future weather years for use in areas such as building thermal simulation.

### **Introduction**

Globally temperatures have increased 0.8 °C since the late 19<sup>th</sup> century and have risen by 0.2 °C per decade over the past 25 years with the 10 warmest years on record all being since 1995<sup>1</sup>. It is very likely that most of the warming has been caused by anthropogenic greenhouse gas emissions and with the current climate change mitigation policies the warming trend is likely to continue with a global temperature rise of 2.8 °C (4 °C) under the A1B (A1FI) SRES emissions scenario<sup>2</sup>. However recent research has suggested that the actual temperature could be much higher<sup>3</sup>.

In the UK the Central England Temperature has increased by about 1 °C since the 1970s with 2006 being the warmest on record<sup>4</sup>. Under the medium emissions scenario (A1B) the UK is projected to warm even further with a central estimate (median) mean temperatures in Southern England up to 4.2 °C warmer and 2.5 °C warmer in the Scottish islands by the 2080s<sup>5</sup>. When translated to the mean daily maximum summer temperature, increases are up to 5.4 °C in southern Britain and 2.5 °C in northern Britain by the 2080s. Furthermore, the warmest day of the summer is projected to increase in the range of 2.4 °C to 4.8 °C depending on location. Under the high emissions scenario (A1FI) the median mean daily summer temperature is projected to increase by up to 5.3 °C while the median mean daily maximum temperature is predicted to be up to 6.8 °C warmer. Without climate change the heat wave of 2003 in Europe is estimated to be a 1-in-a-thousand year event. However modelling by the Met Office Hadley centre suggests this will be a typical summer by the 2040s while in the 2080s it is expected to be anomalously cool. Such extremes will have consequences on the internal environment and on human health<sup>6</sup>.

To look at the risk to the internal environment, the latest probabilistic projections from the United Kingdom Climate Impacts Program (UKCP09) can be used to create probabilistic future weather<sup>7</sup>. UKCP09 contains a weather generator which is able to output both daily and consistent hourly weather data on a 5 km grid over the UK for the historic period (1961-1990) and future time slices in decadal steps from the 2020s up to the 2080s (with

each encompassing a separate thirty year period)<sup>8</sup>. Many thousands of historic and probabilistic future weather years can be created at a high spatial resolution removing the limitation of a lack of observations typically found around the United Kingdom. However, only a few variables are output, namely, precipitation, dry bulb temperature, partial vapour pressure, relative humidity, sunshine fraction, total radiation and potential evapotranspiration.

In this paper we will discuss a method to create future probabilistic reference weather files based on the output of the UKCP09 weather generator. Techniques for the creation of wind data (wind speed and wind direction), atmospheric pressure and cloud cover will be analysed, all of which are required so that the files can be used within thermal modelling software. Finally with the use of thermal models, the outputs of the weather generator will be compared to a set of future weather files created from the morphing procedure of Belcher *et al*<sup>9</sup> and outputs from the UKCIP02 projections<sup>10</sup>. It will be shown that, although the weather files from the UKCIP02 projections lie within the range of the weather generator outputs, the weather generator outputs allow for a much greater spatial resolution and can give a better idea of risk.

### **The Weather Generator**

Based on the UKCP09 probabilistic change factors over land, a stochastic climate change weather tool has been produced by the University of Newcastle to generate weather files with either a daily or hourly time

series<sup>8</sup>. The weather signal is created by using daily precipitation as the primary variable while other variables are created using mathematical and statistical relationships with daily precipitation and the previous day's values. The general procedure uses the baseline climate (1961 – 1990) to calibrate the weather generator rainfall model, then; change factors are applied to generate the future precipitation. Finally the other variables are calculated conditioned by the precipitation and appropriate UKCP09 change factors. The hourly data is then disaggregated from the daily signal using relationships derived from observations. It must be noted that although the climate change information is given on a 25 km grid, the addition of a 5 km grid for the weather generator allows for changes in local topology and is based on observations which have been spatially interpolated onto the same 5 km grid but does not give any further climate information other than the 25 km grid.

The weather generator outputs nine variables for the daily signal: daily precipitation, maximum temperature, minimum temperature, sunshine fraction, vapour pressure, relative humidity, direct radiation, diffuse radiation and potential evapotranspiration (*PET*). Where as the hourly signal contains the variables hourly precipitation, temperature, vapour pressure, relative humidity, sunshine fraction, diffuse radiation and direct radiation. However, to create a weather file of the same format as the Chartered Institute of Building Services Engineers (CIBSE) reference years, wind speed, wind direction, air pressure and cloud cover need to be generated in a

consistent manner with the rest of the weather signal. These variables will be discussed individually below.

Wind speed:

Although there is no wind information as a direct output from the weather generator, the calculation of *PET* requires wind speed. A variant of the Penman-Monteith *PET* developed by the Food and Agricultural Organisation<sup>11</sup> is given by,

$$\text{eqn. 1} \quad PET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273.16} U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)},$$

where  $R_n$  is the net radiation at the crop surface,  $G$  is the soil heat flux,  $T$  is the mean temperature,  $e_a$  is the saturation vapour pressure at the air temperature,  $e_d$  is the actual vapour pressure,  $\Delta$  is the slope of the vapour pressure curve,  $\gamma$  is the psychrometric constant and  $U_2$  is the wind speed at a height of 2 *m*. Since all other variables are either provided as an output or can be calculated, a simple rearrangement of equation 1 can give the daily mean wind speed consistent with the daily weather signal.

To demonstrate this process eight observed example weather years<sup>12</sup> from around the country have been stripped of the wind speed and recalculated using the procedure outlined above as shown by Figure 1. For each day the *PET* is calculated using equation 1 and this value is then used to calculate the daily wind speed. This is not as tautological as might be first thought since for consistency with the weather generator the value of *PET* is output to an accuracy of two decimal places and truncated at zero. It is found that

97 % of the data is within 10 % of the observed data and 94 % of the data is within 5 %. Using linear regression and a least squares fit gives a gradient equal to 0.997 and an  $R^2$  value of 0.995 demonstrating the applicability of the method. There are two causes of error within this procedure. The first error is caused by the truncation of *PET* at 0. The reconstructed wind speed in this case is the wind speed which would give a value of *PET* equal to zero. If the wind speed is found to be less than zero or much greater than that found by observation, the wind speed is recorded as missing. The second error is found when the differential of the *PET* with respect to the wind speed is large. In this case the number of decimal places is not sufficient to accurately calculate the wind speed and the wind speed is recorded as missing regardless of the calculated value. To improve accuracy, the wind speed is interpolated from the previous day to the next in each case.

For the purpose of thermal modelling of buildings an hourly wind speed is required. This can be achieved by comparing the calculated wind speed with daily mean wind speed calculated from hourly observations at the given location<sup>13</sup>. The hourly observed signal, which corresponds to the observed mean wind speed that best matches the calculated value from *PET* is inserted in to the weather file. Although instantaneous values will not necessarily be maintained, the daily, monthly and yearly averages are consistent.

Wind direction:

The outputs of the weather generator have no indication of wind direction and without information about the pressure systems dominating the generated weather it is impossible to calculate the pressure from first principles. To generate a wind direction signal, observational relationships between wind speed, season and wind direction are used to create a probabilistic distribution at the weather station located closest to the weather generator grid square. It is unknown how weather systems will change in the future or the position of storm-tracks will move in relation to the United Kingdom<sup>5</sup>. Current consensus suggests that weather patterns will not change vastly in the future and natural variability is much greater than the effects of climate change. Therefore basing the future wind direction on a probabilistic distribution from the observations is justified. In this method the wind direction is randomly generated every six hours from the probabilistic distribution based on the season and the hourly wind speed. The missing data is then linearly interpolated to generate a full hourly time series. The choice of every 6 hours is used as a compromise to maintain the probabilistic wind direction distribution and to allow realistic hourly changes and is based on a spectral analysis of observed UK wind data.

Figure 2 shows the yearly-observed wind direction distribution for the weather generator base climate (1961 to 1990)<sup>13</sup>, Chartered Institute of Building Services Engineers (CIBSE)<sup>12</sup> test reference year wind direction distribution and a generated wind direction. The generated wind direction is created by stripping out the wind field (wind direction and wind speed) in the test reference year and using the methods described above to recreate an



hourly wind speed and wind direction. Although there are minor differences at each location, the generated wind direction matches the observed weather signal well. The differences are due to the simplistic method used where one hour is not dependent on the next and because the interpolation does not follow the same probabilistic distribution (although this makes very little difference to a thermal model in the UK since the probability of the wind coming from any one direction is small as shown in figure 2). The differences however are small and are not found to be statistically significant. Both the test reference year and generated wind field are just snapshots of the wind field and in the case of the generated wind field are biased by the calculated hourly wind speed. It must also be noted that the test reference years used are based on observations but are based on a different period (typically 1983 to 2004) compared to the base period of the weather generator. The differences in this case are even smaller, showing that weather patterns did not change substantially in this period and the differences result from the natural variability of the chosen observations, which is a subset of the true distribution.

#### Air pressure:

Similar to the wind direction, the weather generator does not report air pressure. The air pressure has little effect on thermal modelling of buildings in terms of over heating risk (since most equations work as a pressure difference across a building) although it does influence the absolute humidity and condensation risk. It is possible to generate a probabilistic value for air pressure from observations but this leaves the questions of over

what time scale should the value be generated (the periodicity of the pressure systems) and on what variables should the pressure be based. This is shown in figure 3, observations of air pressure show no underlying periodicity, i.e. there is no set speed with which pressure systems move across the UK. As stated above, it is unknown how the pressure systems and the position of storm tracks will change with regard to climate change<sup>5</sup> and therefore it is impossible to also know how pressure will relate to the future climate, therefore, for simplicity the pressure will be generated from a distribution relating pressure to the daily mean wind speed and time of year obtained from observations (1961 – 1990)<sup>13</sup>. The periodicity of the generation however is much harder to determine. An hourly time series of pressure for the first quarter of Cardiff's design summer year (January, February and March) is shown in figure 3, which is based on observations. It is clear there are oscillations with many different frequencies present in the time series showing no overall periodic signal and this becomes even more evident with the use of a Fourier transform where the signal is dominated by the many low frequency oscillations on the order of several days with no discrete peaks in the Fourier transform.

Examining the oscillations between days one and five, the absolute change in magnitude is small and the maximum amplitude of the oscillation is less than a 2 % of the peak. This period can be summarised as a succession of low pressure systems passing over the UK but the underlying pressure is still low. For our simple model we are not concerned with the higher frequency signal but the time between the peaks and troughs of the

underlying signal. Smoothing the signal using an FFT filter removing any oscillation of the order of 2.5 days (60 hours) and below, as shown by figure 4, gives a good representation of the true pressure. The average time between the peaks and troughs (average half-wavelength) of the smoothed data is found to be 125 hours. Using similar analysis an average time of 116 hours is found for Edinburgh, 104 hours for London and 117 hours for Manchester. This implies a value between 4.3 and 5.2 days can be used in the simple model. For simplicity we have considered that a pressure randomly generated every 5 days (120 hours) with the probability of a given air pressure occurring with the daily wind speed and season calculated from observations is adequate for use in building thermal simulation codes. Cubic spline interpolation is then used to fill in missing data<sup>14</sup>. Since the relationship between climate change and pressure is unknown this simple approach would seem appropriate.

#### Cloud Cover:

Muneer<sup>15</sup> has derived empirical relationships between the sunshine fraction and cloud cover in the UK. Using the sunshine fraction from the hourly signal, the cloud cover during daylight hours can be generated with 8 Oktas implying no sunshine in a given hour and 0 Oktas when there is a full sunshine hour. All other hours are linearly interpolated.

#### **Creation of Future Weather Years**

Previously, to assess the performance of buildings under a changing climate, UKCIP02 predictions for changes to mean climate were combined with

CIBSE/Met Office weather years to create synthetic weather years to represent the future time slices of the 2020s, 2050s and 2080s. Although four emission scenarios are available; low, medium-low, medium-high and high, the change factors are a single snapshot on a 50 km grid<sup>10</sup>. The outputs of UKCP09 provide climatic information for three emission scenarios; low, medium and high, all decades between the 2020s and 2080s on a 25 km grid resolution<sup>8</sup> (5 km for the weather generator, although, there is no further climate change signal other than that of the 25 km square centred on the same location). The key difference between the two sets of projections is the use of probabilistic information within UKCP09, such probabilities represent a random sampling of a probability distribution function and hence, the likelihood of a certain amount of climate change. At each location (25 km grid square), decade and emissions scenario, 10,000 equiprobable realisations (samples of the probability density function) have been generated relating changes in climatic parameters. This makes the creation of future weather files more complicated than UKCIP02 as now many future weather years can be realised from the vast number of change factors available. The weather generator, for each run, randomly samples from the 10,000 change factors available and creates a stationary thirty year time series, thirty years of naturally varying weather with the addition of a single sample of climate change on top. The UKCP09 weather generator will output 100 randomly chosen samples of climate data chosen from the set of 10,000. One hundred samples results in an hourly time series of 3,000 equiprobable future weather years. However, it is difficult to visualise what the complete set of 3,000 years of data looks like and there is a large

computational burden of using all 3,000 years within modelling software so an appropriate method for the selection of future reference weather years is required.

The current set of CIBSE weather years include Test Reference Years (TRYs) which are required for energy analysis and Design Summer Years (DSYs) which are required for over heating analysis. The TRY is composed of 12 separate months of data each chosen to be the most average month from the 22 years of data (typically 1983 to 2004)<sup>16</sup>. We will only discuss briefly here the method for producing TRY, for further details can be found in the paper by Levermore<sup>16</sup>. The most average months were chosen based on the cumulative distribution functions of the daily mean values of three parameters: dry bulb temperature (DryT), the global solar horizontal irradiation (GIRad) and wind speed (WS). The daily mean values were determined from the hourly values of each of the parameters for all the months in the years considered. The most average months are chosen using the Finkelstein-Schafer (FS) statistic to compare the cumulative distribution functions<sup>17</sup>. The FS statistic sums the absolute difference between the values for each day in an individual month's cumulative distribution function and the overall cumulative distribution function for all the months considered for a weather variable given by,

eqn. 2 
$$FS_{m,y} = \sum_{i=1}^{N_m} \left| CDF_{i,m,y} - CDF_{i,m,N_y} \right|,$$

where  $FS_{m,y}$  is the FS statistic for month  $m$  in year  $y$ ,  $CDF_{i,m,y}$  is the cumulative distribution function for month  $m$ , in year  $y$  and day  $i$ , and  $CDF_{i,m,Ny}$  is the cumulative distribution function for month  $m$  and day  $i$  over all years  $N_y$ . The months with the smallest FS statistic are chosen as the most average. The FS method is superior to just using means to choose the most average as it chooses months with less extreme values that have a cumulative distribution function closer to that of all the years considered. Hence the average month chosen using the FS statistic can be considered representative of all the years. This process is followed for each month of the year for each parameter in turn. For each month,  $i$ , the candidate, most average month for the TRY were assessed from the sum,  $FS_{sum,i}$ , from their FS statistics,  $FS_i$ , to give a weighted index for selection combining all three parameters, Dry bulb temperature (DryT), Global radiation (GIRad) and wind speed (WS) given by,

$$\text{eqn. 3} \quad FS_{sum,i} = w_1 FS_i(\text{DryT}) + w_2 FS_i(\text{GIRad}) + w_3 FS_i(\text{WS}) ,$$

where  $w_1$ ,  $w_2$  and  $w_3$  are weighting factors for each weather parameter. The weighting factors add up to unity and the exact values are chosen depending on each parameters relative importance. Since the candidate month with the lowest  $FS_{sum}$  for WS might not have the lowest FS for DryT the sum is taken. The most average month is the one with the lowest  $FS_{sum}$ , and hence the most average for the three parameters considered. This is done for each month of the year in turn. For the TRY files created for the UK a value of 1/3 was chosen for each weighting factor.

In comparison to the complicated method for selecting the TRY, the creation of a DSY is far simpler as it is a single contiguous year. The CIBSE procedure is to calculate the mean temperature over the period April to September inclusive for each year in the observation series (1983-2004)<sup>16</sup>. The selected year is the year with the third warmest April to September period. This procedure produces a near extreme weather year.

To create future weather years from the weather generator output a similar method is employed to create test reference years and future design summer years. The UKCP09 weather generator produces 100 sets of 30 years on a daily time series. Then using a disaggregation procedure an hourly time series is then produced. Each set of thirty years, although stochastically produced to include natural variability, is stationary with regard to climate change signal incorporated within it. This means that at the beginning of the weather generator run the future climate signal is selected randomly from the probability density function of possible future climates including the inter variable relationships between different weather parameters. So each sample of 30 years includes a different realisation of a future climate. Since the hourly time series is based on the daily time series, the daily values are used within the procedures of creating the future reference years to save computation time. The hourly time series data which corresponds to the daily data is then used in the final reference years.

For each sample of 30 years, the design summer year is calculated in a similar manner to the one used to order the observations. For each year in the set, the mean temperature from April to September inclusive is calculated. The original design summer year was chosen as the third warmest from a set typically of 21 years (i.e the 19<sup>th</sup>) and is the 90<sup>th</sup> percentile. Since the weather generator produces a larger set, to maintain the same relationship the 90<sup>th</sup> percentile is chosen, but in this case this is the fourth warmest April to September period in the thirty year set. The CIBSE test reference year method considers the most average months based on daily means of dry bulb temperature, global solar radiation and wind speed using the FS statistical method. Using the weather generator the mean daily dry bulb temperature is calculated by taking the average of the daily minimum temperature and the daily maximum temperature and the wind speed is calculated from *PET* using a rearrangement of equation 1. For most of the original test reference years, global radiation was not available and was calculated from solar radiation models and the cloud cover and thus, originally cloud cover is used within the FS statistics. This is similar in the weather generator where global solar radiation is not a direct output of the weather generator but calculated from solar models and sunshine hours and therefore the variable sunshine hours is used within the FS statistic for our method.

By finding the most average 12 months within each set of thirty years (in the case of the TRY), the tails of the distribution (extremes) of natural variability are removed leaving an idea of the climate signal in an average



year while making an estimate of a near extreme year (design summer year) gives an idea of the extremes of natural variability on top of the climate signal. The end result is a set of 100 test reference years and 100 design summer years, one from each of the thirty-year samples, each with a different climate signal.

### **Creation of probabilistic weather data**

When the weather generator samples from the complete probability density function, the climate change factors (differences between the base climate from 1961 to 1990 and the required future time period) include many inter-variable relationships. For the weather generator this includes monthly, seasonally and annual changes to precipitation, relative humidity, mean air temperature, maximum air temperature, minimum air temperature and total cloud cover. For a realisation of a future climate these inter-variable relationships must be maintained. Also a probabilistic weather file must give careful consideration to changes over the entire year. For instance, considering just air temperature; a yearly change in mean air temperature does not give an idea of the distribution of the change in mean monthly air temperature. An overall warming of 2°C over the year could be the result of all months being slightly warmer or a colder first 6 months combined with extreme positive change factors for the second six months could leading to the same overall yearly change. This could raise problems when the weather files are used, especially if only part of the year is under consideration, i.e. summer overheating.

To create probabilistic weather years, which maintain the climate signal and keep a consistent weather signal over the year, appropriate percentiles can be chosen using pointwise intervals for each month using a single climatic variable. If each variable is ranked separately and combined, although the central estimate for each variable would be used, it would discount joint probabilistic information. i.e. combining the 50<sup>th</sup> percentile of mean monthly temperature change with the 50<sup>th</sup> percentile of relative humidity change could give an unrealistic climate change as they may not be physically consistent. In this paper we will consider pointwise intervals on the mean monthly temperature only. It is just as valid to use any of the other variables as discussed above dependent on which variable is required for the analysis of risk but for simplicity we are considering mean temperature only. For both the sets of 100 design summer years and 100 test reference years each month is ordered according to the mean monthly temperature (the average of the mean daily temperatures over that month), ranked from lowest to highest and then the required percentile (e.g. 50<sup>th</sup>, 90<sup>th</sup> etc) are selected. The process is repeated for each month with data selected at the required percentile to produce either a probabilistic test reference year or probabilistic near extreme weather year as required. This selection procedure is illustrated in figure 5. For every month the mean monthly temperature is ordered and the required percentile is selected (10<sup>th</sup>, 50<sup>th</sup> and 90<sup>th</sup> percentiles are shown in figure 5). The other variables, which correspond to this value of mean monthly temperature, are then also taken as the complete data file for the month. The months with the corresponding

hourly time series are then joined together to form the future weather year using the method outlined by Levermore<sup>16</sup>, i.e. from the set of 100 TRY files ordered by mean monthly temperature the 50<sup>th</sup> percentile January is joined to the 50<sup>th</sup> percentile February etc to create a composite year. In this methodology the Probabilistic Test Reference Year and Probabilistic Design Summer Year are both composite years. Using this method the temperature series show a clear trend where the mean monthly temperature is always greatest for the 90<sup>th</sup> percentile and the 50<sup>th</sup> percentile is the central estimate and always above the 10<sup>th</sup> percentile as shown by figure 5. However, no trend can be found for the other variables as shown for the mean daily relative humidity. Although the 90<sup>th</sup> percentile of mean temperature change for January is much greater than the 10<sup>th</sup> percentile by 5.4°C the corresponding difference for relative humidity is -0.62% with no trend between percentiles throughout the year. This method gives temperatures across the year, which are consistent (i.e median January followed by a median February etc) but maintains the climate signal of the variables. Using this method it is extremely unlikely that the concurrent months occur from the same generated test reference year or design summer year (with 100 different samples, there is a 1 in 10,000 chance of a median January followed by a concurrent median February) but does give a good indication of a median temperature change for the future. This method ensures that the whole year is 'median' (50<sup>th</sup> percentile) eliminating extremes for the given percentile. In this method using a high percentile test reference year such as the 90<sup>th</sup> gives an indication of the extent of likely future warming (UKCP09 defined the 90<sup>th</sup> percentile as unlikely to be greater than) and likewise the

10<sup>th</sup> percentile give an idea of the likely minimum change (unlikely to be less than) with current theories and models. Using this method a 90<sup>th</sup> percentile design summer year gives a near extreme weather year in terms of natural variability (90<sup>th</sup> percentile of natural variability) with a near extreme climate signal. The complete method describing how to generate future weather files from the UKCP09 weather generator is summarised by the flow diagram in figure 6.

### **Comparison of Generated Weather and UKCP02 within a Thermal Model**

To further test the validity of creating future weather files using the UKCP09 weather generator, a selection of future design summer years (DSY) and test reference years (TRY) for the 2050s and 2080s were compiled into a format read by common building simulation software (.epw). Simulations were performed using a thermal model of a typical new-build house (constructions details can be found in the appendix) using an industry standard dynamic thermal modelling program (IES<sup>18</sup>). The future DSYs and TRYs were compared to the future DSY and TRY files currently available from CIBSE<sup>12</sup>, compiled using the morphing method of Belcher *et al*<sup>9</sup> and the UKCIP02 climate change data<sup>10</sup>. The model used includes dynamic opening of windows based upon internal temperatures and occupancy, in this case assumed to be a professional couple with no children. Airflow through window openings is calculated using a zonal airflow model to calculate bulk air movement in and through the building

(Macroflo), driven by wind and buoyancy induced pressures across the building, this requires knowledge of both wind speed and direction. It should be noted again at this point that both the weather generator and the climate change values required for morphing are based upon the climate of the period 1961-1990, whereas the CIBSE DSY's and TRY's are based upon a later period (the exact period for a given location is stated within the file header). Hence, the morphing of DSY and TRY data could result in an over estimate of future climate change. However, at present there is no other accepted reference point for comparison. Simulations were performed for 5 different percentiles of TRYs and DSYs (10%, 33%, 50%, 66% and 90%) for Edinburgh, London and Manchester for the time periods 2050's and 2080's for the high emissions scenario (A1FI) using the method described above. These files were then compared to the CIBSE future files (UKCIP02) for the same period, locations and emissions scenario.

Figure 7 shows the distribution of heating energy requirement for the house. As can be seen from the figure the weather generator TRY files show a distribution of monthly heating energy requirement, which is similar to that produced by the CIBSE future TRY. It also demonstrates that the 90<sup>th</sup> percentile TRY uses the least heating energy in every month as expected due to warmer external air temperatures.

The distribution of mean internal temperatures for all the different weather generator files and the CIBSE future files for Edinburgh is shown by Figure 8. The shape of the distribution of the different percentiles can be seen,

indicating that the shape of the CDF curve of the sorted weather generator data is translated into the internal environment in the thermal simulation. It is interesting to note that the CIBSE future TRY produces results towards the higher percentiles of the weather generator as shown by figures 7 and 8. This may be an indication of the over estimation mentioned earlier as a result of the files being morphed since the climate may have changed between the 1961-1990 period and the period from which the TRY is chosen, typically 1983-2004.

By plotting the change in mean internal air temperature against the mean external temperature we see that the weather generator data exhibits the same linear trend as observed by Coley and Kershaw<sup>19</sup> with morphed UKCIP02 climate data as shown by figure 9. The trend of the data shown in figure 9 is highly linear with a correlation coefficient  $R^2 > 0.98$ . The scatter observed here is due to natural weather variability in the weather generator files on top of the climate signal. In the previous study morphed files were investigated where the procedure stretches and transforms the observed weather. As a consequence the weather patterns for morphed files do not change in the morphed weather files only the underlying climate data. Again, we note that the CIBSE future files which are based upon UKCIP02 rather than UKCP09 lie on the same linear trend. This demonstrates that the weather files created by the weather generator give an internal environment which is comparable to the weather files created from UKCIP02 (and the morphing procedure). The key advantage of UKCP09 and the weather

generator is the greater spatial resolution since it is not dependent on an observed time series and the use of probabilistic information to inform risk.

## **Conclusion**

In this paper we have shown that hourly future weather files created using the UKCP09 weather generator can be used for thermal simulation of buildings. The results have been found to be consistent with the currently available CIBSE future DSY and TRY files, which are based upon the morphing methodology of Belcher *et al*<sup>9</sup> and the UKCIP02 climate data. In all cases the results obtained from a dynamic thermal model of a typical new build house are consistent with the CIBSE future DSY and TRY files lying within the distribution of weather generator files. The method for creation of these files can be summarised as:

- Run the UKCP09 weather generator to generate 100 samples of 30 years of hourly future weather data for a given decade, location, and emission scenario.
- Calculate missing variables; wind speed, wind direction, air pressure and cloud cover.
- Generate 100 TRY and DSY files, one from each sample of 30 years (ordering the natural variability).
- Order each month of the 100 TRY and DSY files according to ascending monthly mean temperature.

- Using pointwise intervals choose the relevant percentiles required (to order the change in climate), i.e. the 90<sup>th</sup> percentile January, February, March etc. and combine these months to form a composite year (at this point we have future weather files similar to the .try and .dsy weather files available from CIBSE<sup>12</sup>).
- Convert the weather files into the format required by building thermal simulation packages (i.e. .epw).

The use of future weather files created using the UKCP09 weather generator are free and carry no copyright allowing the use of this powerful tool to create probabilistic future weather files for use by architects and engineers as well as academics.

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### **Appendix**

Building Construction (defined outside to inside):

Ground floor:- soil, brickwork (outer leaf), cast concrete, EPS slab, chipboard, carpet. U-Value = 0.2499 W/m<sup>2</sup>K

Ceiling/floor:- carpet, chipboard, cavity, plasterboard. U-Value = 1.2585 W/m<sup>2</sup>K



Internal walls:- plasterboard, cavity, plasterboard. U-Value = 1.6598

W/m<sup>2</sup>K

External walls:- brickwork, EPS slab, concrete block, plaster. U-Value =

0.3495 W/m<sup>2</sup>K

Flat Roof:- U-Value = 0.2497 W/m<sup>2</sup>K

Glazing:- 6mm glass, 12mm cavity, 6mm glass. U-Value (including frame)

= 1.9773 W/m<sup>2</sup>K

Occupancy: the house is assumed to be owned by a professional couple with no children.

Windows openings, for the houses windows are assumed to open 75% when the internal temperature reaches 23°C during occupied hours.

Heating, the heating set point is set at 18°C and is only on during occupied hours (unlimited capacity heating).

Glazed fraction of façade ~7%

Floor areas, 135.29 m<sup>2</sup>

Ext wall area, 178.56 m<sup>2</sup>

Volume, 331.39 m<sup>3</sup>

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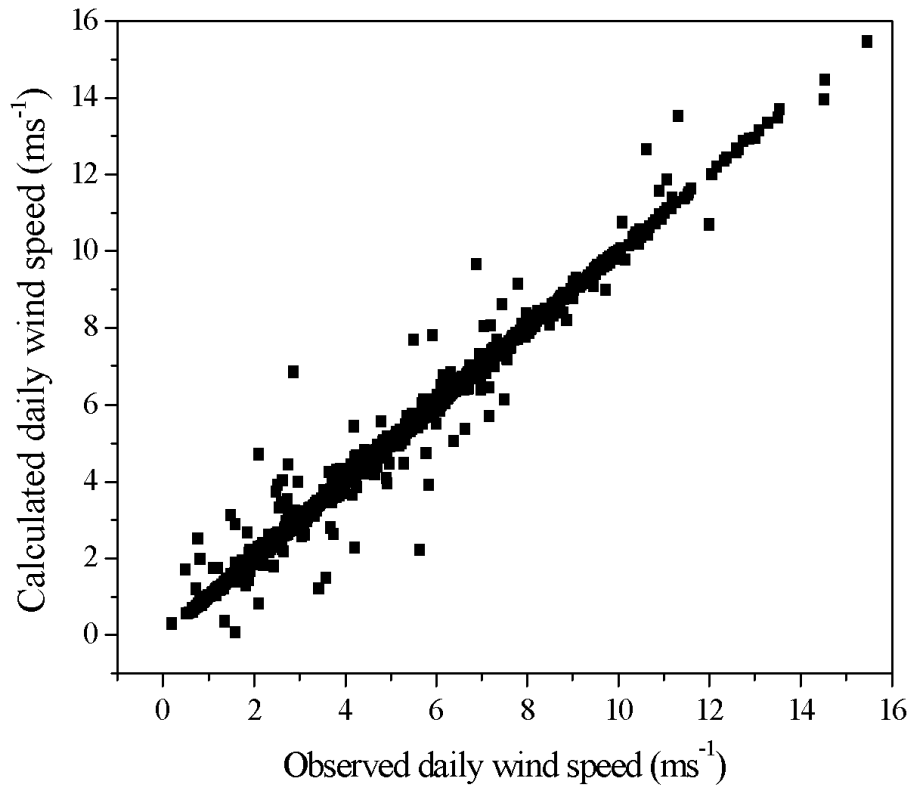


Figure 1 Observed mean daily wind speed against the calculated mean daily wind speed for eight different locations around the United Kingdom (2920 days in total).

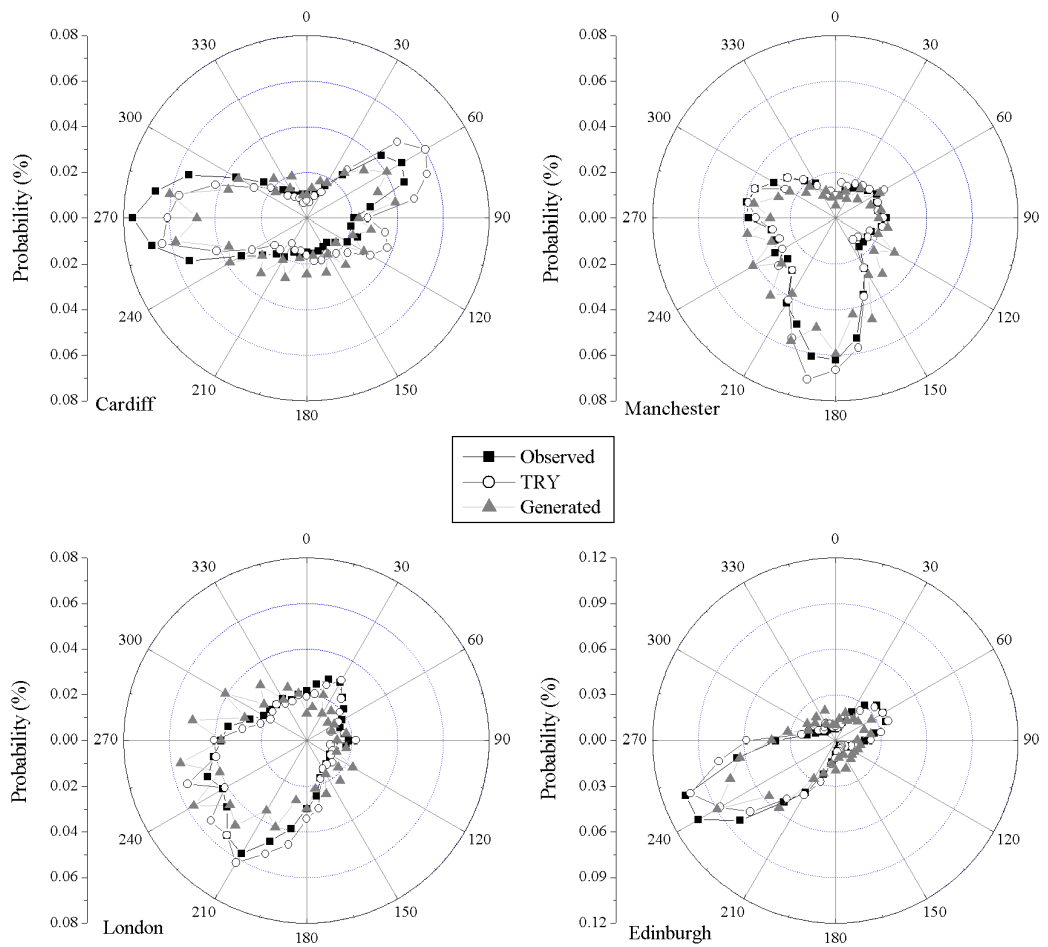


Figure 2 Polar plots of wind direction against probability for Observed weather (1961 – 1990), CIBSE test reference year and generated wind directions for four different locations from across the United Kingdom.

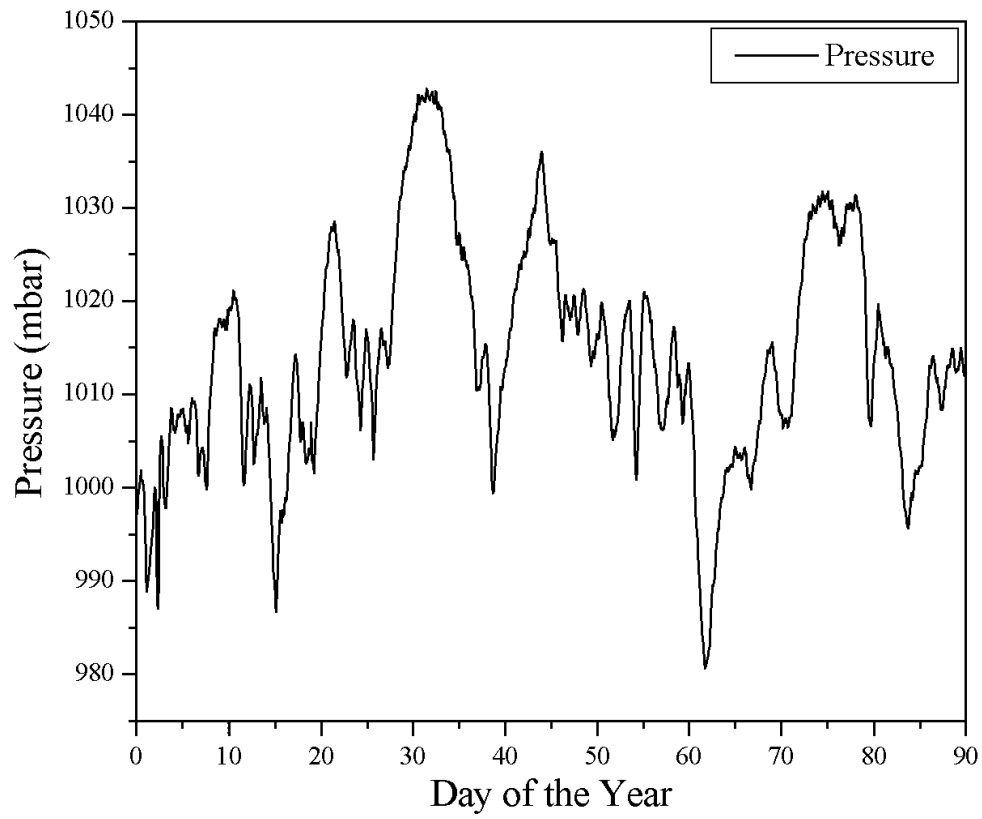


Figure 3 Observed air pressure for the first three months of the Cardiff design summer year (1999).

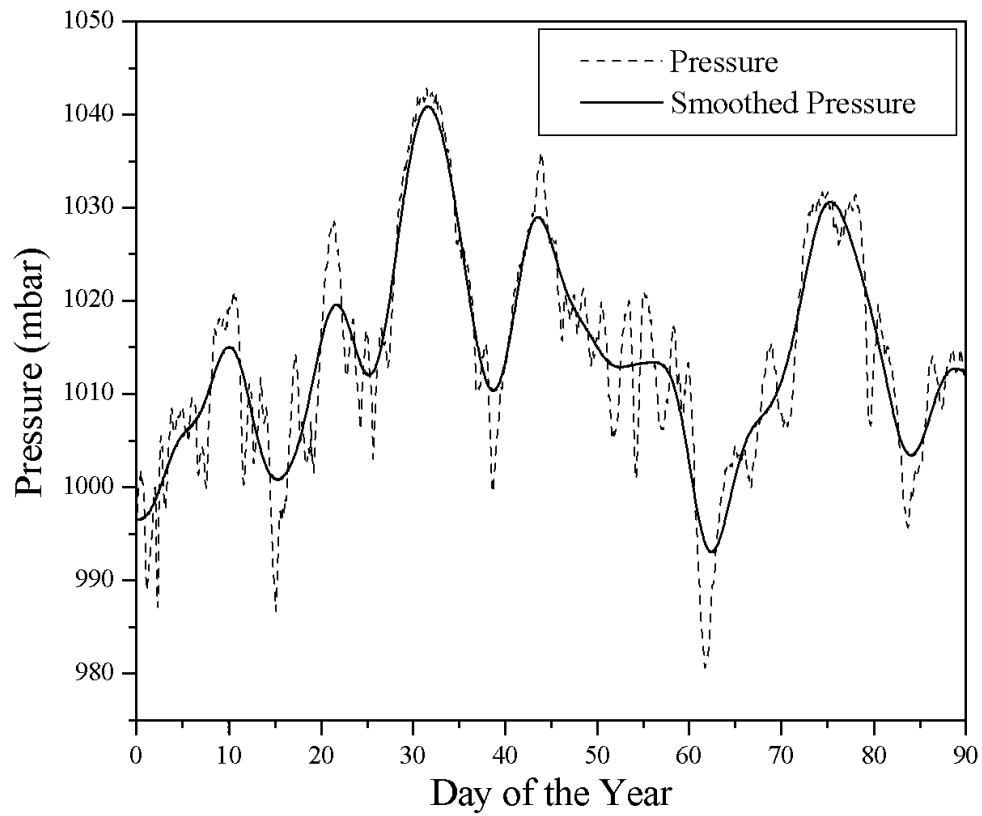


Figure 4 Smoothed air pressure for the first three months of the Cardiff design summer year. The actual observed time series is shown as a dotted line.

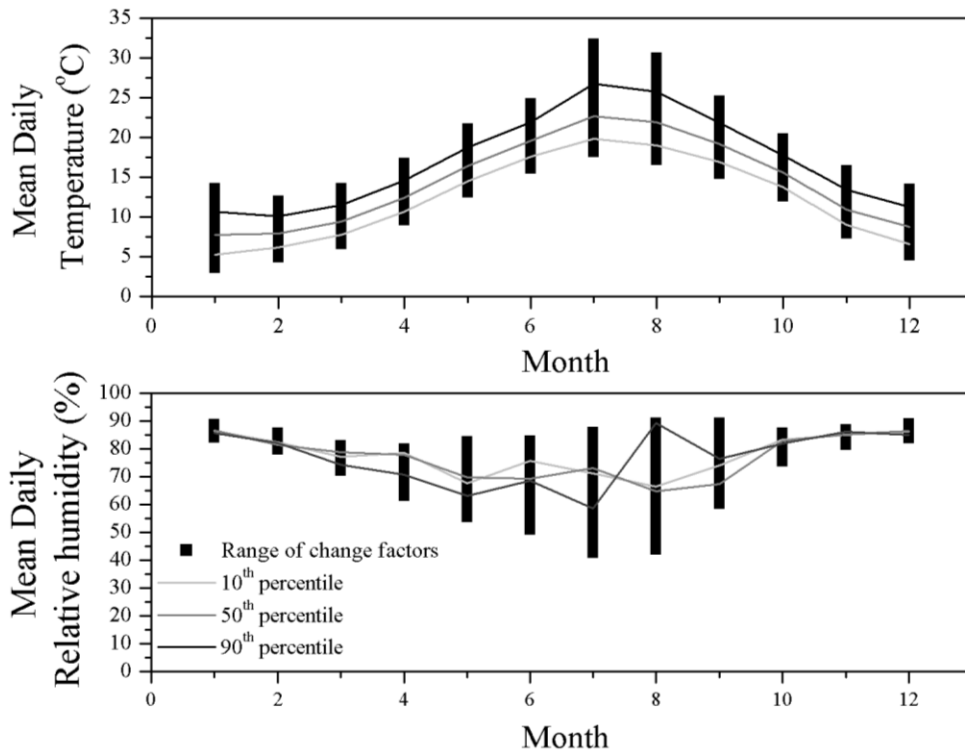


Figure 5 Graphs showing the extent of change factors for the mean monthly temperature and relative humidity. The lines demonstrate the selection procedure and have been ordered in terms of the mean temperature. Although the 90<sup>th</sup> percentile of mean temperature change is always much greater than the 10<sup>th</sup> percentile, the corresponding selection of relative humidity does not follow the same trend.



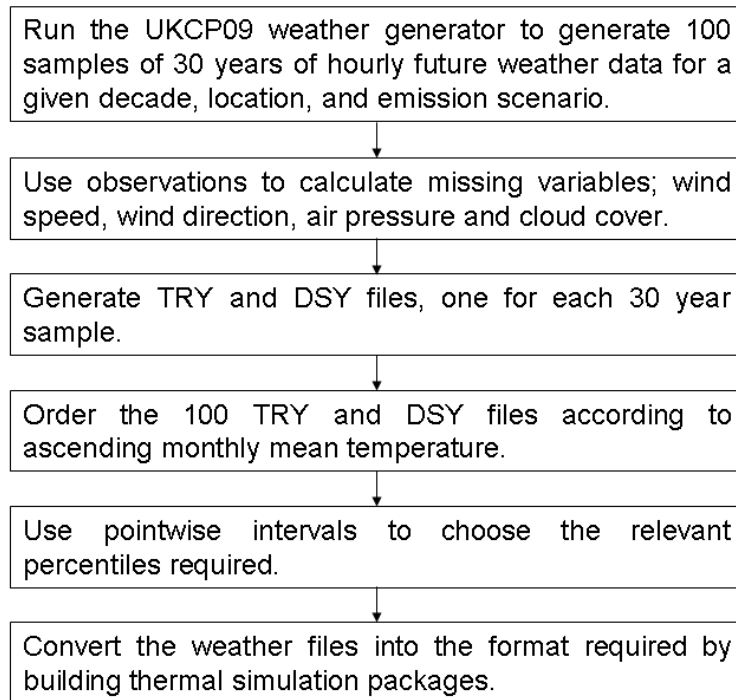


Figure 6 Flow diagram showing the method of creating future probabilistic weather years from the UKCP09 weather generator

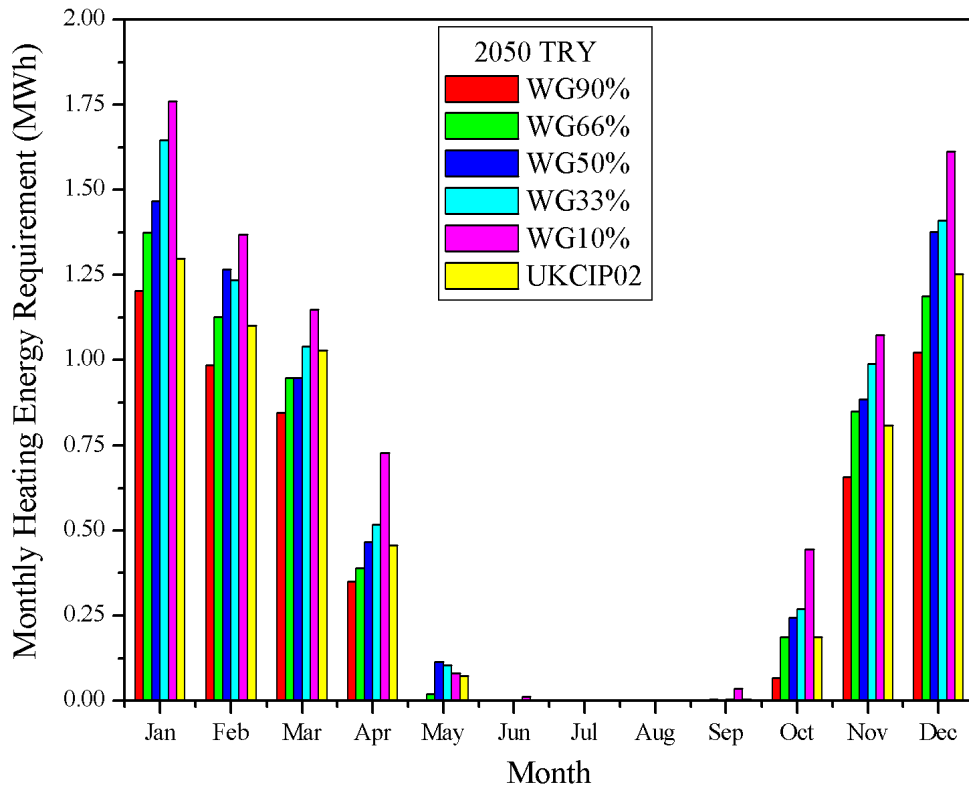


Figure 7 Plot of the monthly heating energy requirement of the building for the different weather generator (WG) TRY files and the CIBSE future TRY (UKCIP02). Data shown is for London in 2050.

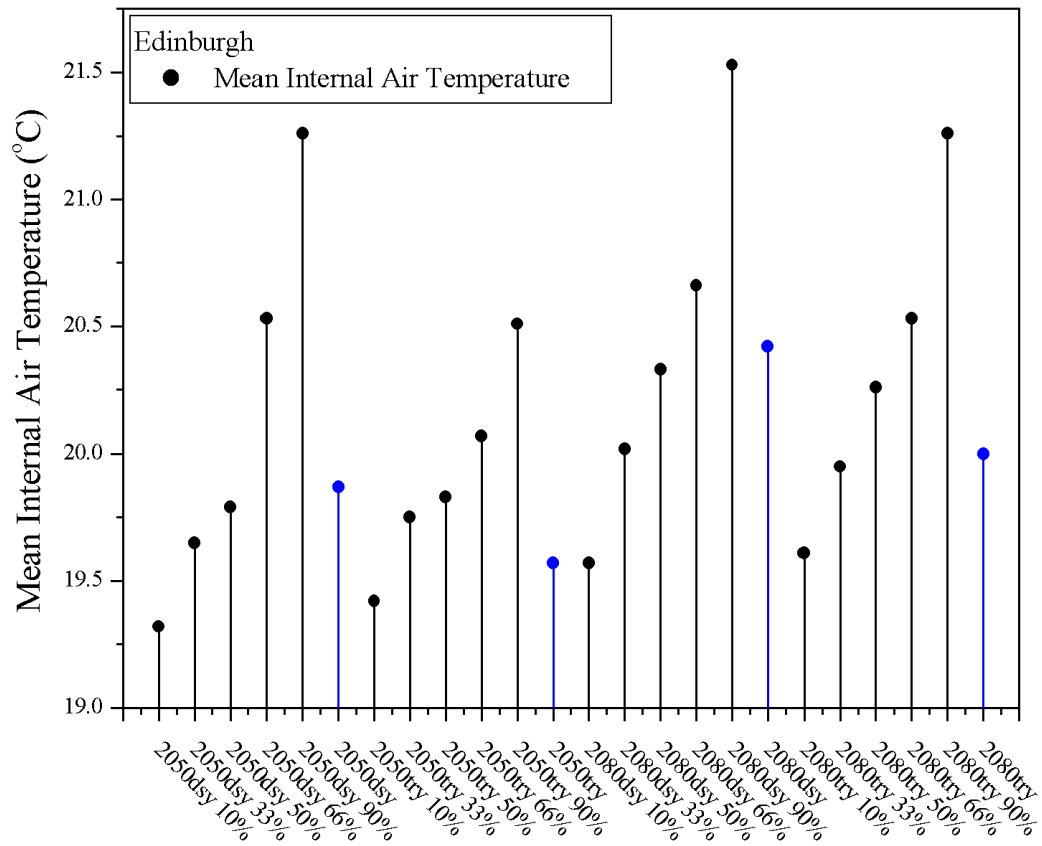


Figure 8 Plot of the mean internal air temperature for the different future DSY and TRY percentiles (black circles) and the equivalent CIBSE future files (blue circles). Data shown is for Edinburgh.

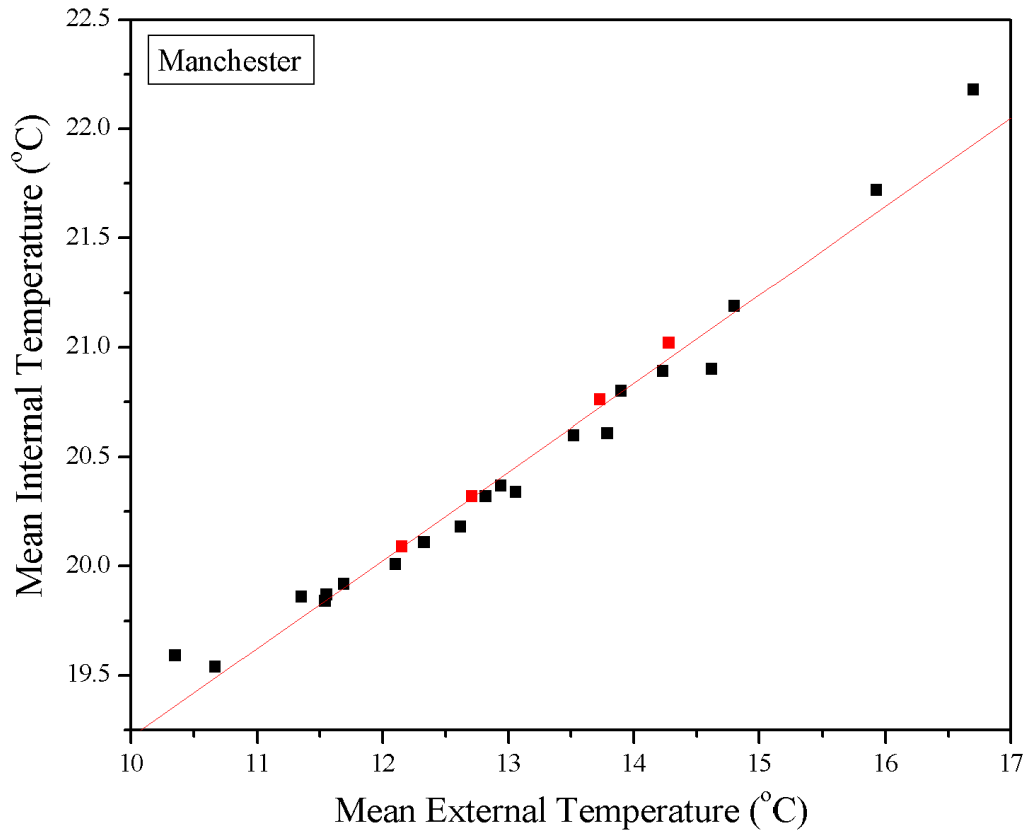


Figure 9 Plot of mean internal temperature versus mean external temperature, showing that the linear relationship previously identified with UKCIP02 data<sup>10</sup> holds true with the UKCP09 weather generator. The data shown for all weather generator DSY and TRY files, both 2050's and 2080's for Manchester (black squares), also shown are the corresponding CIBSE future files (red squares).