Assessing the risk of climate change for buildings: a comparison between multi-year and probabilistic reference year simulations

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Abstract

Given a changing climate, there is a need to provide data for future years so that practicing engineers can investigate the impact of climate change on particular designs and examine any risk the 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 release of the UK Climate Projections (UKCP09) [1], and the publication of a methodology for the creation of probabilistic future reference years using the UKCP09 weather generator [2], it is possible to model future building performance. However, the collapse of the distribution of possibilities inherent in the UKCP09 method into a single reference year or a small number of reference years, potentially means the loss of most of the information about the potential range of the response of the building and of the risk occupants might be subject to. In this paper we model for the first time the internal conditions and energy use of a building with all 3000-example years produced by the UKCP09 weather generator in an attempt to study the full range of response and risk. The resultant histograms and cumulative distribution functions are then used to examine whether single reference years can be used to answer questions about response and risk under a changing climate, or whether a more probabilistic approach is unavoidable.

Introduction

Reference weather years are used by the building simulation community to model the likely internal environment within a building and its energy use. These reference years consist of data files that contain a list (usually on an hourly time step) of measured common weather parameters such as atmospheric pressure, temperature and wind speed. Reference weather years are published for many parts of the world, with the exact detail depending on the professional body or national institute that has assembled them; however, in all cases they attempt to represent many years worth of weather with a single year. In the UK these take the form of the Chartered Institute of Building Services Engineers (CIBSE)[3] Test Reference Year (TRY).

The TRY is a composite year comprising of the most average months drawn from ~23 years worth of data typically spanning 1982-2004. A full methodology detailing the creation of these files can be found in the paper by Levermore [4]. The use of a single reference year would seem a sensible approach as it greatly reduces the computational effort required in modelling a building and hence the cost of the design process. Since

this approach was first used, computers have become a lot faster but models and codes more complex, thus the approach has remained the standard way of assessing building performance.

This approach cannot be used to compute risk: given a single representative year it is impossible to assess quantitatively how likely any conditions are, nor the return periods of extreme events. Likewise, when addressing the question of mortality or morbidity from thermal stress it is peak temperatures and reduced diurnal cycles sustained over several days that are important and the reference year may not be extreme in this regard at all. Reference years are usually assembled from a consideration of around 20-30 years of observed data. This is a relatively short period for the identification of means and very short for the identification of extremes. The use of a weather generator capable of producing several thousand years worth of weather data seems ideal for the study of complex questions such as high peak temperatures and reduced diurnal cycles sustained over several days and their respective return periods. The UKCP09 weather generator used for this study is provided with a threshold detector to allow complex questions such as the number events where the maximum daily temperature is above 30°C and the daily minimum temperature does not fall below 15°C is sustained for at least 3 days. In a previous study [5] a direct comparison between the conditions within a series of buildings when modelled by a continuous twenty to thirty year record of weather to those produced by using single reference years selected from the same data set was made, i.e. the posterior statistic (for example energy consumption) was compared with the statistic generated by using a climatologically representative year. The purpose of this paper is to apply a similar method to probabilistic future reference years and the base data from which they are compiled.

Climate Change
One of the reasons for completing this work is the question of climate change. In building physics, most research on the topic focuses mainly upon the mitigation of climate change, i.e. the reduction of greenhouse gas emissions. Other studies have studied the adaptation of the built environment to climatic change, aiming to reduce the risk of building failure and reduce the impact on the building occupants. But how do we quantify the risk?

Due to the nature of the models used to produce climate change projections there is a level of uncertainty in the possible levels of future climate change. In the UK this uncertainty has been represented in the latest set of future climate projections UKCP09 [1] released by the UK Climate Impacts Programme. These projections are probabilistic because multiple runs of climate models from several different countries were used to create a range of possible climatic futures. The results were then used to create probability density functions (PDFs) for a variety of climatic variables. These PDFs can be sampled at will to produce a large number of possible climatic futures.

By definition, we do not have a record of future weather, and therefore files to allow the simulation of buildings under future climates must be created. One method [6,7] is by using mathematical transformations of current reference years given knowledge of future climate typically expressed as monthly changes to the current climate [1]. Another

method is to use a weather generator to produce hourly results. This second method has the ability to produce a vast number of example years, which could either be used to produce one or more reference years [2], or the complete set could be used to study a wide range of questions about the energy consumption and internal environment. Potentially such a set, because it contains a very large number of years, would include extreme years that would thereby allow one to address return periods for extreme events. Given the implied increase in computation time and cost, this method is unlikely to become an industry-standard approach using common thermal models unless it is known that the approach gives very different results from the standard approach. This work is an attempt to examine the size of the difference.

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 [8]. 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 weather. 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 climate change factors [1]. The hourly data are then disaggregated from the daily signal using relationships derived from observations. 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*). Whereas the hourly signal from the weather generator contains the variables hourly precipitation, temperature, vapour pressure, relative humidity, sunshine fraction, diffuse radiation and direct radiation. 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. This can be achieved using the methods described in [2]. This methodology allows the creation of probabilistic future reference years chosen from the 3000 years output by the UKCP09 weather generator. These files are probabilistic and should encompass the range of possible values giving an indication of the range of possible overheating risk etc.

The data output by the UKCP09 weather generator takes the form of 100 runs, each run represents a sampling of the climate data PDFs, each sample is then augmented with 30 years of weather data to create a total of 3000 years. To create the probabilistic reference year files each sample of 30 years is used to create a test reference years using the methodology of Levermore [4]. This results in 100 test reference years, the probabilistic reference years were constructed using pointwise intervals of monthly mean dry bulb temperature. This method orders the weather data for all 100 Januarys (one for each sampled run of the weather generator) according to the monthly mean air temperature, lowest to highest. The different percentiles are then selected and are designated as 10%, 33%, 50%, 66% and 90% according to their relative position; this is repeated for each

month in turn. This means that the median 50th percentile January is combined with the median February, March etc. More information about this process can be found in Eames et al [2].

Method
3000 example weather years were created using the UKCP09 weather generator. The resultant weather files are representative of the possible climate in the 2050's using the medium emissions scenario (a1b) [9] as an example. 3000 years represents a single output of the UKCP09 weather generator when generating hourly time series. This represents 100 samples of possible climate change randomly chosen from a PDF with each sample containing 30 years of hourly weather data. Weather data for the city of Plymouth in the UK was chosen for this study. Missing variables are created using the same method employed when creating the reference years [2]. These where applied to two thermal models of a mechanically ventilated office, one of heavy-weight construction and one light-weight, both complying with 2002 UK building regulations. Because of the computational and setup time it would have taken to process such a large number of weather years for each design using an industry standard model (such as IES, TAS etc), a lumped-parameter dynamic model was used.

The Excalibur (Exeter Calculation in Building Thermal Response) [10] software uses the structural element time constants given by the classical stored-to-transmitted energy ratio, to calculate five parameters describing the thermal response of each zone within a building. The parameters describe the thermal mass of the building structure and of the air it contains, the heat loss by thermally rapid response paths (ventilation, glazing etc), heat flow from the interior of the building to the thermal mass and from the thermal mass to the outside. The resulting model has two time constants (per zone) derivable from the parameters. The fast time constant is related to the thermal capacity of the enclosed air and is usually less than one hour. The slow time constant is typically of order of magnitude tens of hours and is associated with the thermal inertia of the building structure. Because many of the calculations are completed analytically rather than numerically, the runtime for a year of simulation is only a fraction of that required by industry-standard codes.

Probabilistic reference years [2] (available from www.ex.ac.uk/cee/prometheus) compiled from the same 3000 example years were also used to drive the simulation of the building. These simulations should allow a direct comparison between the reference years and all the 3000 files output by the weather generator. Due to the methodology used to create the probabilistic reference years, they are an exploration of the possible change in climate rather than weather. The weather patterns represented in the probabilistic reference years should be representative of the period, similar to how a test reference year is representative of the current weather. The reference years were also run through an equivalent thermal model created using the IES virtual environment software [11]. The office under consideration conforms to 2002 UK building regulations, has an occupancy of 96 people, lighting gains of $12W/m^2$ and other gains of $15W/m^2$, the heating set point is 19°C.

Results

The following graphs show the distribution of mean internal and external temperatures (Figure 1), maximum occupied temperature (Figure 2), heating energy usage (Figure 3), and annual heating energy use. Also shown are results from the five probabilistic reference year files (triangles). This allows us to compare the reference years against the CDF curves. As mentioned above the probabilistic reference years were constructed using pointwise intervals of monthly mean dry bulb temperature and are designated as 10%, 33%, 50%, 66% and 90% according to the cumulative distribution function (CDF) percentile used to create the file [2]. The horizontal separation of the triangles from the curve is a measure of the difference produced by the two methods.
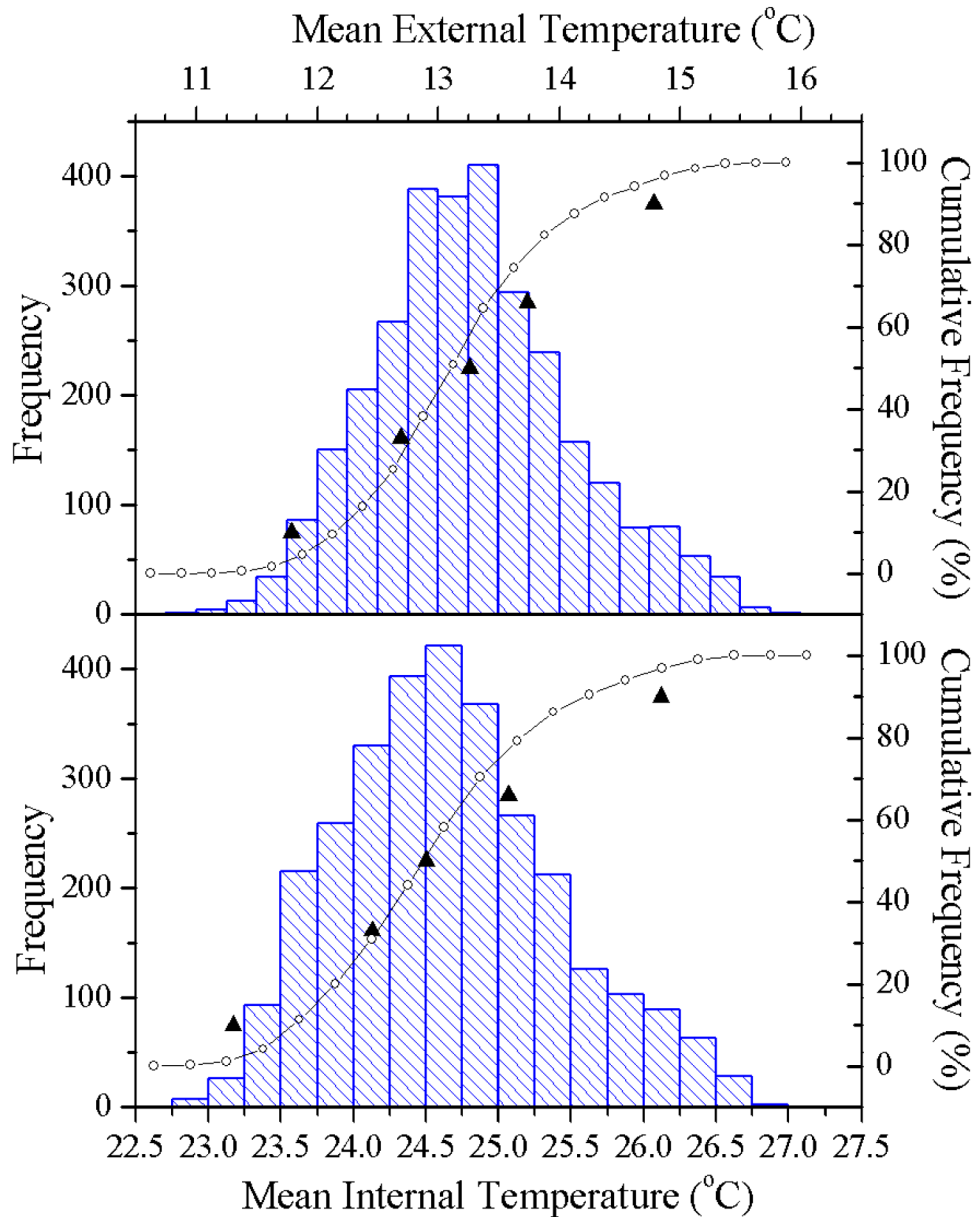

Figure 1 Histograms of mean external (top) and internal (bottom) temperatures for the 3000 weather files overlaid with their respective CDF curves. Internal data shown for the

heavy-weight structure. Also shown are the five results from the 10th, 33rd, 50th, 66th and 90th percentile reference years. The horizontal offset of these from the CDF curves is a measure of the difference given by the two methods.
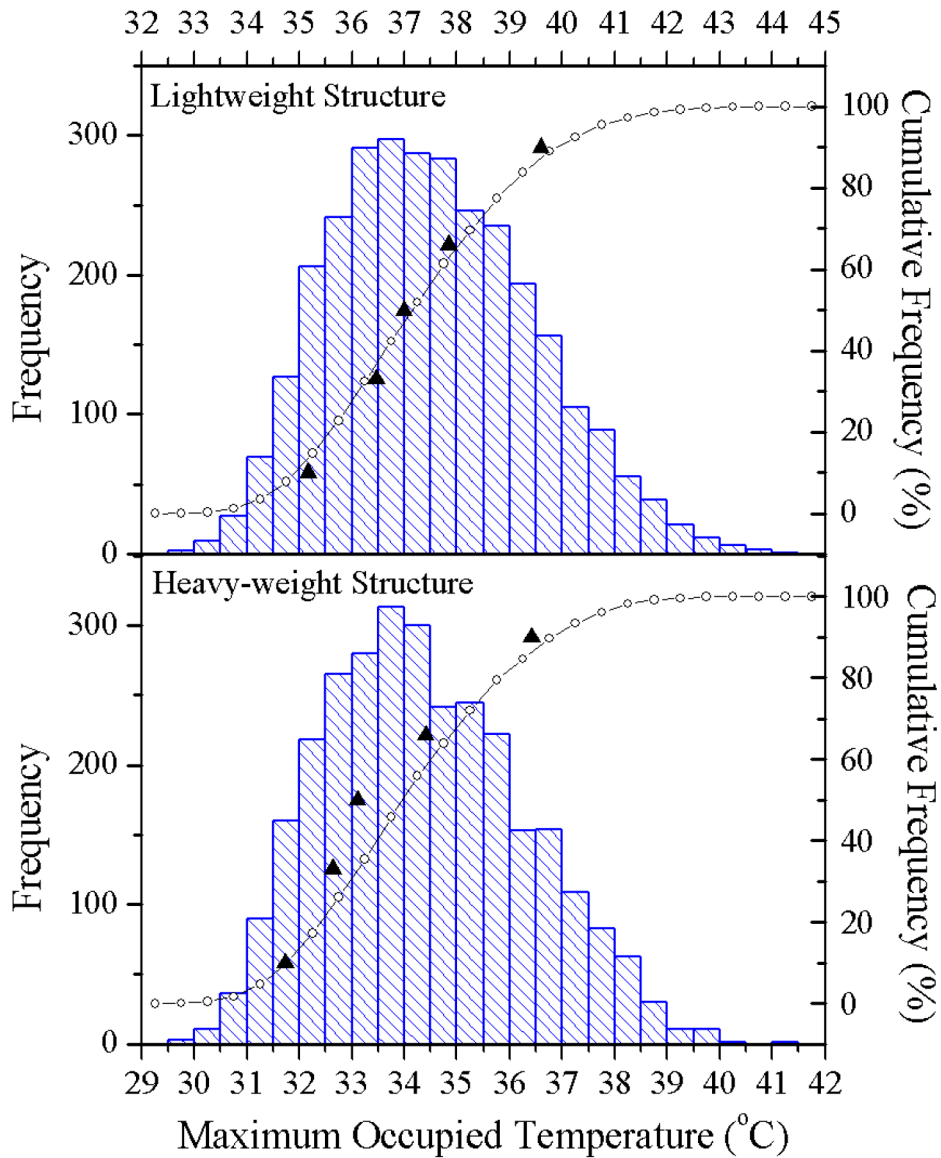

Figure 2 Histograms and CDFs of the maximum occupied temperature within the heavy-weight structure (lower pane) and for the lightweight structure (upper pane) for the 3000 weather files. Results from the probabilistic reference years for the heavy-weight and lightweight structures are shown as black triangles. Again, the offset between the triangles and the CDF curves is a statement of the difference produced by the two methods.

From these graphs we see that there is considerable variation in both the internal and external environments. The histograms of internal and external temperature shown in figure 1 are similar in shape and width indicating that the external air temperature is a major driver of the internal temperature. Figure 2 shows unsurprisingly that the lightweight structure reaches higher temperatures than the heavy-weight structure. This has a knock-on effect for other building parameters such as heating energy usage and hours of overheating. The histograms of heating energy usage (figure 3) for the heavy and lightweight structures are similar in shape with a slight shift in the distribution towards greater energy usage for the lightweight structure. This information could not be conveyed using standard non-probabilistic reference years. However, the results for the probabilistic reference years shown in the figures 1, 2 and 3 follow well the distribution of values created by the simulation of the 3000 example years. This is can be shown by examining the horizontal separation between the CDF curves and the probabilistic reference year values. Table 1 summarises the deviation in temperature or heating energy usage from the CDF values. We see that the two methods are always in agreement to an accuracy of 0.79°C or a heating energy use of 477 kWh. Interestingly, the higher percentile files do not necessarily give the greatest deviation.
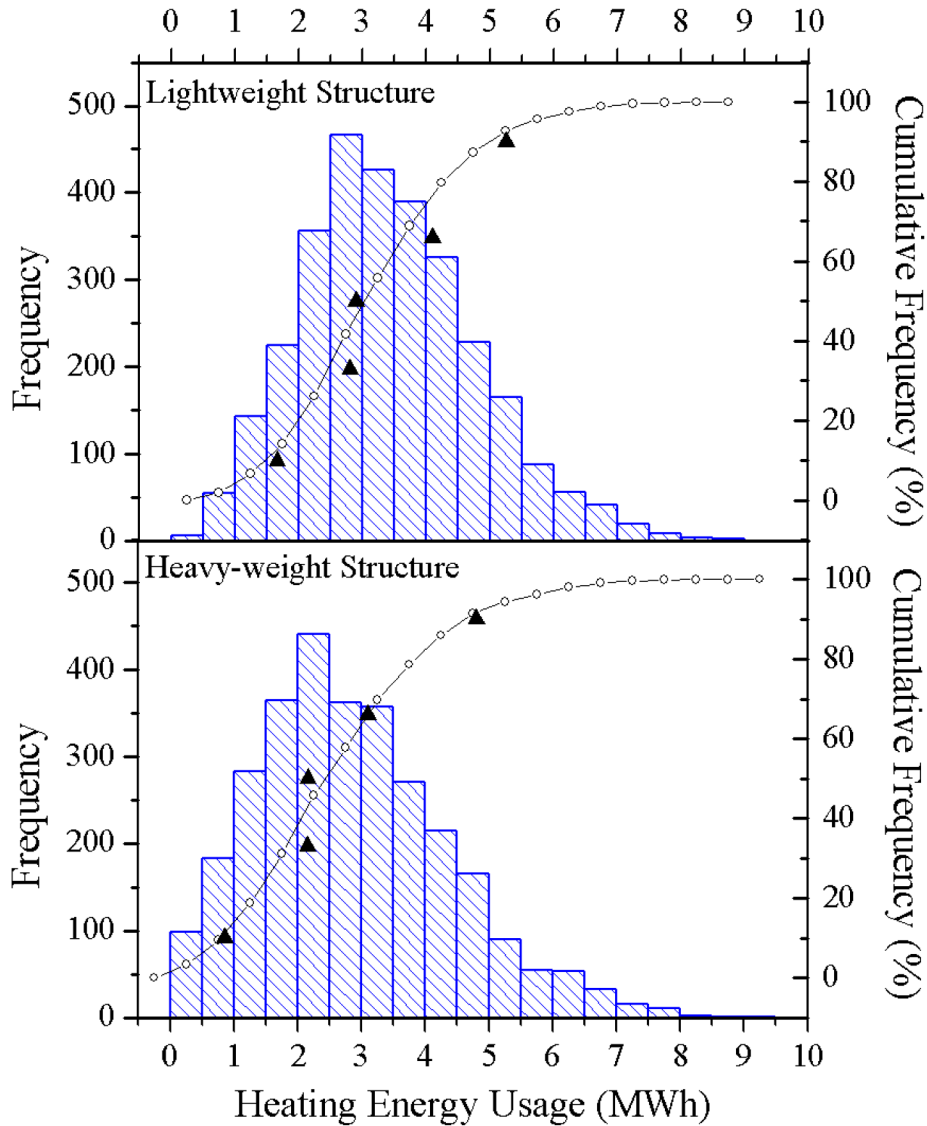
Figure 3 Histograms and CDFs of the heating energy usage generated by the 3000 weather files for the heavy-weight (bottom) and lightweight (top) structures, results using the probabilistic reference years are shown by black triangles.

Deviation from CDF	Probabilistic Reference Year Percentile				
	10%	33%	50%	66%	90%
External mean temperature °C	-0.32	-0.07	0.15	0.32	0.50
HW mean internal temperature °C	-0.38	-0.04	0.02	0.27	0.50
LW max occupied temperature °C	0.25	0.15	-0.15	-0.15	-0.29
HW max occupied temperature °C	-0.05	-0.44	-0.79	-0.49	-0.39
LW heating energy difference kWh	199	358	-79	477	306
HW heating energy difference kWh	40	358	-239	-40	200

Table 1 The deviation of the PRY files from CDF curve values for the data shown in figure 1, 2 and 3.
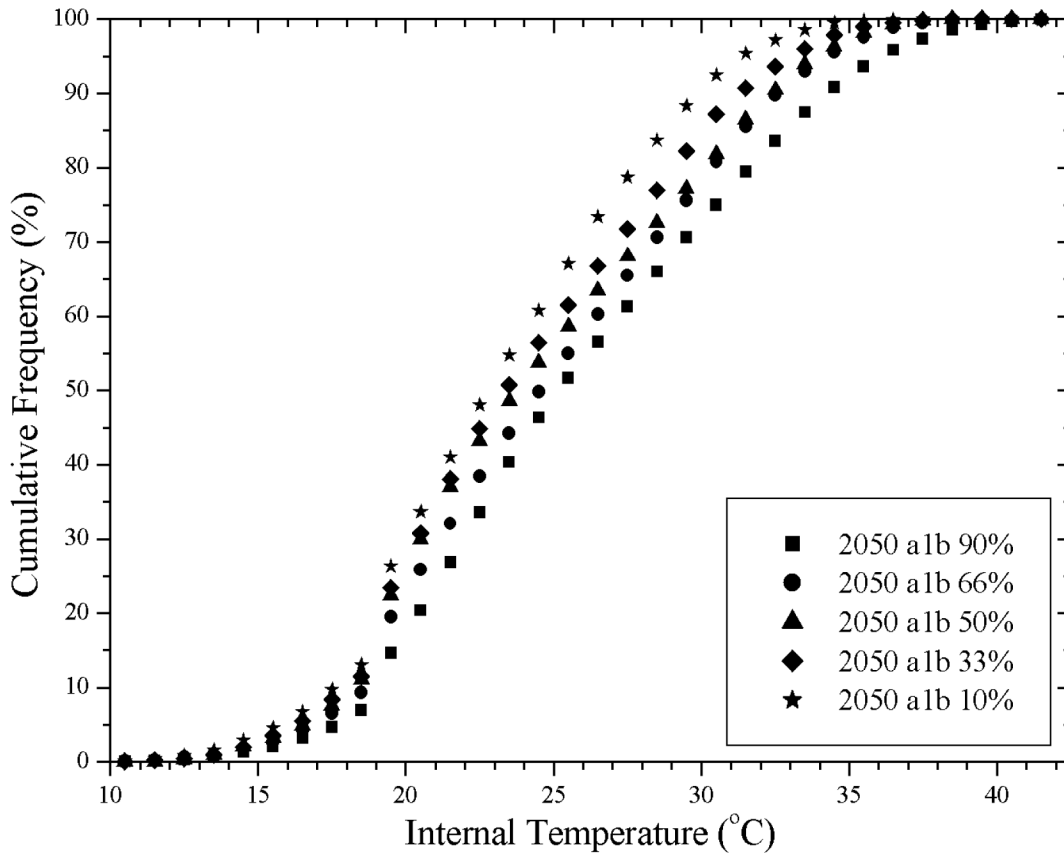

Figure 4 CDFs of hourly mean internal air temperatures of the five probabilistic reference years showing the propensity for overheating as calculated by IES. CDF data shown comprises a whole year (8760 values) for the lightweight structure.

Figure 4 shows CDFs of the internal temperatures for the lightweight office as predicted by the IES software. The different probabilistic reference years display different levels of overheating. For example using the a1b 10% file the internal temperature exceeds 28°C for approximately 20% of the time but using the a1b 90% file exceeds 28°C approximately 35% of the time and this is likely to be within occupied hours. Table 2 shows the hours of overheating for the different probabilistic reference years as predicted by IES for the different offices. Unsurprisingly the lightweight office overheats more than the heavy-weight.

	Heavy-weight Structure				Lightweight Structure			
	>25°C	>26°C	>27°C	>28°C	>25°C	>26°C	>27°C	>28°C
10%	1270	1136	988	741	1363	1163	957	779
33%	1376	1251	1146	1026	1482	1318	1149	979
50%	1512	1381	1232	1086	1582	1405	1257	1108

66%	1582	1436	1326	1159	1697	1530	1354	1189
90%	1708	1526	1413	1290	1805	1628	1469	1315

Table 2 Hours of overheating during occupied hours for the heavy-weight and lightweight structures for the different reference year percentiles.

Figure 5 shows results obtained from the UKCP09 threshold detector [8], which can be used to study the likelihood of complex events using weather generator data. In this case the data is for the occurrence within the 3000 example years of a heat wave: defined by conditions when maximum daily temperature is greater than 30°C and minimum daily temperature is greater than 15°C, for a minimum of three consecutive days. This is one method of using the 3000 example years to answer complex questions about the future climate and the impacts on buildings and their occupants. Such complex questions cannot be answered using probabilistic reference years.

The method for the calculation of the summary statistics shown in figure 5 is as follows:
1. For each weather generator run of 30 years, the total number of threshold events that are recorded in each year is summed.
2. Then the average for that particular run in the 30 year period is calculated by dividing the sum of threshold events from 1 above, by 30.
3. Doing 1 and 2 above, for each of the 100 runs, we can then add the total up for the 100 years and calculate the mean by dividing by 100. This is what provides the mean value reported in the summary statistics file and shown in figure 5.
4. The minimum, and maximum values reported are simply the minimum and maximum values found in the 100 values, calculated as a result of having completed steps 1 and 2 for all 100 simulations.
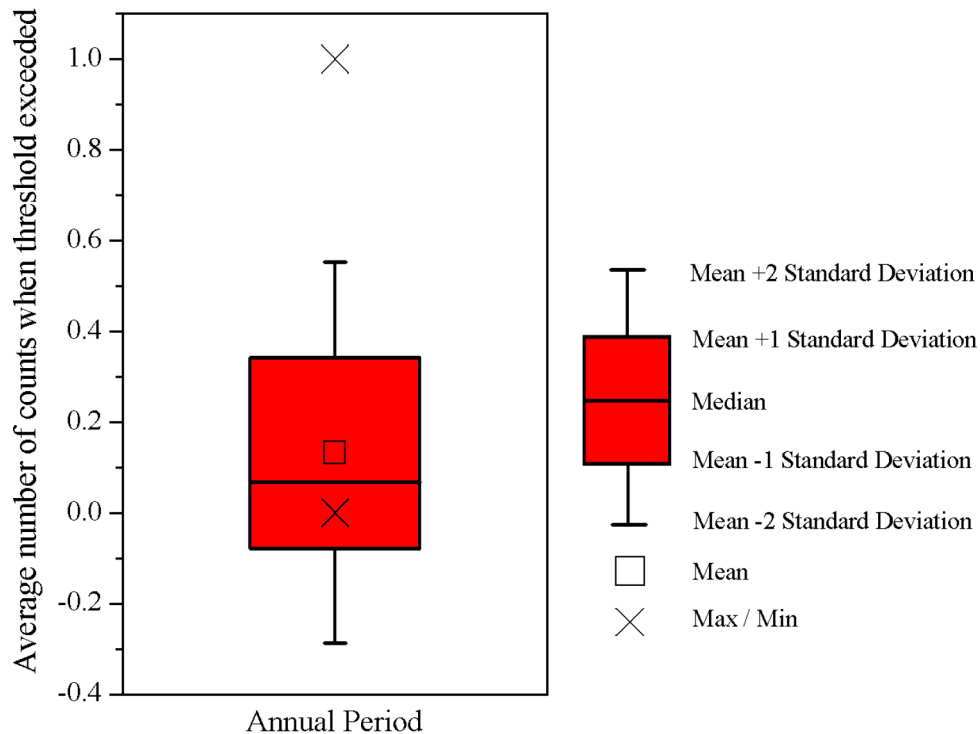
Figure 5 Output of the UKCP09 threshold detector, data shown is number of occurrences of heat waves in the 3000 example years.

Discussion
In this paper we have shown that 3000 example years output from the UKCP09 weather generator can be used to explore the range of possible climatic conditions both within and outside a building. The 3000 example weather files can be used to provide information about the shape of the PDF curves for different climatic variables and answer, for example, complex questions such as, what is the probability that the maximum temperature is >30°C and minimum daily temperature is >15°C, for a minimum of three consecutive days. Other complex questions could be asked using the results of the thermal model to study the likelihood of complex events within the building. Such data could be used to study for example the impacts of temperatures on the productivity of office workers or the likelihood of heat stress and other heat related illnesses.

The 3000 year run of the thermal model used took less than 2 hours on a modern computer but only because a lumped parameter dynamic model was used. If industry standard software (such as IES or TAS) were used the simulation of 3000 files would have taken approximately 500 hours, this time obviously varies with the complexity of the model and more complex buildings may take much longer. Thus the use of all 3000 years is likely to be seen as impractical by practicing engineers, unless they have access to much faster codes or computers. Hence there is the need to know how well the probabilistic reference years represent the results space.

The data shown in figure 1 shows that the thermal mass of the building moderates the external temperatures as expected. The mean external temperature of the 3000 files spans 5.5°C while the mean internal temperatures of the 3000 files spans only 4.75°C. While only the mean external temperature is shown other weather variables included in the weather file can be examined if required. Comparison of the five probabilistic reference years with the histogram and CDF of the 3000 example years shows that the external data matches very well indicating that the probabilistic reference years can be used to explore the range of temperatures. The probabilistic reference years span a slightly greater range of temperatures than the equivalent percentiles as indicated by the CDF of the 3000 example years. This is not overly surprising due to the method used to create the probabilistic reference years. However, it is important to note that the probabilistic reference years are a good match for the distribution of the 3000 years and that the deviation from the values indicated by the CDF curve is small with a maximum deviation of 0.5°C for both internal and external temperatures (table 1).

Figure 2 shows the distribution of maximum occupied temperatures for both the heavy-weight and lightweight offices for the 3000 example years. The distributions are similar in shape and width with the heavy-weight structure displaying a marginally wider range of temperatures. Comparison between the CDF curves and the values predicted by the probabilistic reference years shows that they are in good agreement with a maximum deviation of 0.79°C for the lightweight structure. Figure 3 shows that distribution of heating energy usage for the different buildings and the associated reference year values. The span of the possible heating energy usage projected by the 3000 example weather years is from less than 1 MWh to nearly 10 MWh. It can be observed that once again the reference years are a good representation of the 3000 files from which they were created with a maximum deviation of 477 kWh for the lightweight structure.

Figure 4 shows the CDF curves of the internal temperature for the lightweight office building as predicted by IES for the five probabilistic reference years. These results were compiled from all 8760 hourly values of mean internal temperature for each of the five probabilistic reference years. The data shown in figure 4 allows the likelihood of internal conditions exceeding a set temperature to be assessed. High internal temperatures can have serious implications for the health, comfort and productivity of the building occupants, so it is prudent to assess levels of risk. The data shown in Table 2 shows the occupied hours of overheating for the two offices, this form of data is easily obtained from thermal modelling software packages such as IES or TAS. However, it is hard to build up a picture of the level of risk using this method. By plotting the resultant data as a CDF curve we can see that the probability of internal temperatures exceeding 28°C is ~20% for the 10th percentile file increasing to ~37% for the 90th percentile file, while the 50th percentile file which represents the central estimate of possible climate change (under the a1b emissions scenario) exceeds 28°C for ~30% of the time. Information about maximum temperatures and the hours of overheating gives little indication of the shape of the distribution and the associated risk. Using probabilistic reference years should allow multiple building designs to be assessed by the level of risk they pose to the occupants. The probabilistic reference years are designated as the 10th, 33rd, 50th, 66th and 90th CDF percentiles (ordered according to monthly mean external air temperatures), this

means that there is a possibility that external temperatures and consequently any overheating within the building could be greater than that predicted by the 90th percentile file or conversely, less than that predicted by the 10th percentile file. The ability to effectively map out the whole distribution of possible climatic futures as predicted by the UKCP09 weather generator using only a few probabilistic reference years is a powerful tool when considering the impacts of climate change on buildings.

The data shown in figure 5 shows that complex statistical questions (in this case the number of heat wave events) can be asked of the 3000 years of data. Figure 5 shows that the mean number of heat wave events per year from the 3000 years worth of data (100 sampled runs of 30 years) is approximately 0.1. Similarly the data also shows that the maximum average number of heat wave events per year in a single run (30 years) is ~1. The data shown in these box and whisker plots could be used to create probability density functions for particular events and assess relative probabilities. Such techniques could also be used to assess the likelihood of complex statistical events within buildings however this was not attempted in this paper due to the large amount code that would have to be rewritten to enable this within the Excalibur software. It should be noted here that due to the imperfect nature of the weather generator and the data output, extreme care should be taken when assigning return periods and return periods longer than 5-years should be used with caution [8]. Hence it can be concluded that unless such complex statistical questions and return periods are required for the internal environment of a building and the modeller has access to very fast computer codes, the 3000-year approach using the full output of UKCP09's weather generator is impractical. For more typical questions (e.g. total hours over 28°C, annual energy use) the probabilistic reference years provide a very close match to the distribution produced by the 3000-year approach and hence the use of all 3000 years is unnecessary.

Summary

The outputs of the UKCP09 weather generator can be used to compile both large sets of example weather years as well as probabilistic reference weather files compatible with building thermal simulation programs. These files can be used to assess the variability of different variables and the associated risks. The data presented in this paper shows that almost the full range of values predicted by the 3000 files can be estimated using the probabilistic reference years created using the methodology described in reference [2]. These probabilistic reference years can be used to assess the risk of building failure and the risk to building occupants using significantly less computational time than required to simulate all 3000 files output by the UKCP09 weather generator.

Acknowledgements

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