The impact of different weather files on London detached residential building performance—deterministic, uncertainty, and sensitivity analysis on CIBSE TM48 and CIBSE TM49 future eather variables using CIBSE TM52 as overheating criteria

Bahadori-Jahromi, Ali ORCID logoORCID: https://orcid.org/0000-0003-0405-7146 and Amoako-Attah, Joseph (2016) The impact of different weather files on London detached residential building performance—deterministic, uncertainty, and sensitivity analysis on CIBSE TM48 and CIBSE TM49 future eather variables using CIBSE TM52 as overheating criteria. Sustainability, 8 (11). p. 1194. ISSN 2071-1050

http://dx.doi.org/10.3390/su8111194

sustainability

MDPI

Article

The Impact of Different Weather Files on London Detached Residential Building Performance—Deterministic, Uncertainty, and Sensitivity Analysis on CIBSE TM48 and CIBSE TM49 Future Weather Variables Using CIBSE TM52 as Overheating Criteria

Joseph Amoako-Attah and Ali B-Jahromi *

Department of Civil and Built Environment, School of Computing and Engineering, University of West London, London W5 5RF, UK; Joseph.Amoako-Attah@uwl.ac.uk

* Correspondence: ali.jahromi@uwl.ac.uk; Tel.: +44-0208-231-2270

Academic Editor: Umberto Berardi

Received: 18 August 2016; Accepted: 8 October 2016; Published: 22 November 2016

Abstract: Though uncertainties of input variables may have significant implications on building simulations, they are quite often not identified, quantified, or included in building simulations results. This paper considers climatic deterministic, uncertainty, and sensitivity analysis through a series of simulations using the CIBSE UKCIP02 future weather years, CIBSE TM48 for design summer years (DSYs), and the latest CIBSE TM49 DSY future weather data which incorporates the UKCP09 projections to evaluate the variance and the impact of differing London future weather files on indoor operative temperature of a detached dwelling in the United Kingdom using the CIBSE TM52 overheating criteria. The work analyses the variability of comparable weather data set to identify the most influential weather parameters that contribute to thermal comfort implications for these dwellings. The choice of these weather files is to ascertain their differences, as their development is underpinned by different climatic projections. The overall pattern of the variability of the UKCIP02 and UKCP09 Heathrow weather data sets under Monte Carlo sensitivity consideration do not seem to be very different from each other. The deterministic results show that the operative temperatures of the UKCIP02 are slightly higher than those of UKCP09, with the UKCP09 having a narrow range of operative temperatures. The Monte Carlo sensitivity analysis quantified and affirmed the dry bulb and radiant temperatures as the most influential weather parameters that affect thermal comfort on dwellings.

Keywords: building simulation; operative temperature; CIBSE overheating criteria; future weather; uncertainty and sensitivity analysis; CIBSE TM48; CIBSE TM49; CIBSE TM52

1. Introduction

There is a direct bearing of changes in climatic conditions on buildings in relation to buildings energy performance and thermal comfort. In building performance practice, it is imperative to secure reliable formatted multi-year weather files which have been prepared from reliable meteorological predictions to assess the energy performance and overheating risk in buildings [1–5].

In 2002, the Department for Environment, Food and Rural Affairs as part of the UK climate impacts program commissioned and funded the work on the UK climate projections, UKCIP02 [6]. This fourth generation of climate change is deterministic climate projection, which gives a single outcome for a specific variable at a given location [7]. The Climate Change Scenarios for the United Kingdom: The

UKCIP02 Scientific Report acknowledged that the UKCIP02 scenarios do not incorporate the entire range of possible future scenarios, as no probabilities were appended to the four climatic scenarios [6].

In 2009, the UK Climate Projections (UKCP09), the fifth and most comprehensive prediction of climate change projections was published by the United Kingdom Impacts Programme which has a collective contribution from the Met Office Hadley Centre, UK Climate Impacts Programme and over thirty different organisations [7] to provide practical support for effective adaptation to organisations whose work and functions are underpinned by climate change [7]. One of the key differences between the UKCIP02 and UKCP09 projections lies in the methodologies used in producing them. The UKCP09 scenarios are underpinned by probabilities of climate change based on quantification of the known sources of uncertainty. This aspect of the UKCP09 scenarios makes it supersede the UKCIP02 scenarios that are based only on a variant of one (Met Office) model [7].

The UKCP09 has deferring properties and characteristics when compared with UKCIP02. One key difference is that the UKCIP02 data generation is based on four of the six marker projected emission scenarios of the IPCC Special Report on Emission Scenarios (SRES) of high, medium-high, medium-low, and low, which underpin the United Kingdom's Meteorological Office Hadley Centre (MOHC) Climate Change Model (HadCM3) future global climate model (CIBSE 2009). On the other hand, the UKCP09 future projected emissions scenarios are underpinned by three of the six marker emission scenarios of the IPCC Special Report on Emission Scenarios of A1F1, A1B, and B1 scenarios, namely high, medium, and low emission scenarios, respectively [6,8,9].

In addition, the UKCIP02 variations are mapped to the MOHC HadRM3 regional climate models (RCM) to simulate climatic variations on a 50 km grid RCM spatial resolution [6]; UKCP09 scenarios, however, include pattern-scaling and down scaling uncertainty and have a greater RCM spatial resolution of 25 km, grid coupled with a 5 km resolution for a weather generator [7].

The output of climate models of the UKCIP02 and UKCP09 cannot be directly used in building simulation practice. Downscaling of annual, seasonal, or monthly outputs to hourly data is required. In 2008, the Chartered Institution of Building Services Engineers (CIBSE) released two sets of future weather files, the test reference years (TRYs) and the design summer years (DSYs) based on the UKCIP02 climate projections. The methodology used to produce the CIBSE future weather files was the 'morphing' time series adjustment [10] methodology that adjusted the historic weather files to the climate projection [8,11]. The first TRY typical year was based on direct observation of weather source baseline period of 1983–2004 [8]. These weather data sets are based on observed measurements and are deterministic in nature [11,12]. With the release of UKCP09 probabilistic climate projections, it was imperative to develop new methodologies that take cognisance of the probabilistic nature of the UKCP09 climate projections to advance the improvement of building simulation weather files. The Engineering and Physical Sciences Research Council (EPSRC) in 2008 funded four projects to utilize the probabilistic UKCP09 to produce weather files for building simulation analysis. CIBSE, on the other hand, have sought potential alternatives (with the morphing methodology in view) to offer weather files for building simulations based on the UKCP09 probabilistic climate projections [11].

The CIBSE TRY weather files as representative weather years for building energy performance analysis are not suitable for overheating analysis; hence, the DSY weather files were developed [13]. The method for developing the DSY weather files is simple when compared with that of the TRY weather files [13]. The CIBSE DSY is a single complete weather year which gives a near extreme weather year. CIBSE has currently developed a new methodology for producing DSYs based on the UKCP09 probabilistic climate projections for use in building simulations. This offers a better correlation between the likelihood of the DSY occurring and the likelihood of building overheating [14]. These new DSYs for London take into consideration the geographical location, the impact of the urban heat island effect, and future climate change, when performing building simulation summer overheating analysis for London [14,15]. The new DSY weather files for London include two additional weather stations of London Weather Centre (LWC) and Gatwick Airport (GTW). This offers different levels of overheating risk assessment for different locations in London, namely urban, intermediate urban, and suburban locations. Moreover, the new DSYs include the two additional years of 1976 (a year with two-week extreme heat wave) and 2003 (a year with more persistent warm summer) as the earlier DSY based on 1989 weather data from London Heathrow Airport (LHR) does not represent a sufficiently warm year for overheating risk assessment in buildings [14]. In addition, it considers three greenhouse emissions scenarios of high, medium, and low, three future periods of 2020s, 2050s, and 2080s, and differing levels of probabilities of 10th, 50th, and 90th percentiles [14,15].

1.1. Justification for the Choice of CIBSE Weather Files

Over the years, different approaches for developing weather data series for building performance analysis have been developed [7,16]. In the UK, basically two differing methodologies stand out in creating hourly weather files for use in building simulation practice; the 'morphing' methodology which is the current industrial standard by CIBSE, which adjusted the historic weather files to climatic projections, and the development of various probabilistic projections of hourly weather data sets by the use of the UKCP09 weather generator.

The UKCP09 weather generator is a stochastic tool that uses daily precipitation to create other weather outputs of daily and hourly variables on a 5 km grid for a historical period of 1961–1990 [7]. This offers an advantage due to greater spatial resolution. In addition, the weather generator is suitable for future TRY and DSY weather data sets for building performance analysis [11]. However, the CIBSE weather data sets developed using the morphing methodology are based on observed climatic periods and thus have limited uncertainties which could affect the baseline weather data [13]. Without the implementation of change factor corrections, the CIBSE weather data sets could result in overestimating future climate change variations due to changes in differences of climates reference points: 1961–1990 for the weather generator and 1983–2004 for the earlier CIBSE historic TRY and DSY weather files [11,13].

The choice of the CIBSE morphing methodology as against the weather generation data is based on its reliability [14]. The weather generator does not produce extreme events [11]. The weather generator output of weather data sets years is not as warm in terms of the Weighted Cooling Degree Hours (WCDH) criterion used in the historical data development of the new CIBSE DSYs. This is because the 'extremes of the temperature distribution are not clustered together into particular warm years to the extent as they are in the observed data' [14].

Although the monthly average climate over the years changes, one advantage of the morphing methodology in the non-variant underlying characteristics of the TRY and DSY weather data sets, which facilitates a direct comparison between the present and future building performance analyses. On the other hand, there are differences in basic weather characteristics such as the timing and severity of warm spells between the timelines in using the weather generator [11]. Furthermore, the current CIBSE DSY weather data sets for London consider the urban heat island effects in future weather files, whilst this consideration is absent in the UKCIP09 weather generator.

The use of the weather generator to statistically produce many thousands of historic and probabilistic future weather data at a high spatial resolution provides the significant advantage of a better idea of a complete data set for overheating risk assessment when compared with the observable weather data [17]. The weather generator has an advantage over the morphing methodology. It produces certain weather variables in place of missing data [11] when considering observed data independently. However, the many files generated pose a computational challenge to resources not readily available in building simulation practices [11,13].

A readily acceptable methodology should produce an output of weather data sets that is consistent with currently used data sets and augment the use of standardised weather data sets for use in building energy and thermal performance analysis. The weather generator's outputs of daily precipitation, partial vapour pressure, relative humidity, maximum temperature, minimum temperature, sunshine fraction, direct radiation, and potential evapotranspiration are insufficient for use within thermal simulation for building energy and thermal performance analysis. Key missing parameters such as wind speed, wind direction, atmospheric pressure, and cloud cover are essential in creating weather files of the same format, as is used in CIBSE weather data sets for building simulation software [11,13,17].

Although the weather generator method is more versatile than the morphing method, in terms of observed data and location, the large amount of weather data produced is of a disadvantage in simulation practice [16]. The CIBSE weather files based on the morphing methodology are used in this work due to the consistency between the present available observable historic weather files and those of the future files and a platform for direct comparison of standardised weather data sets for energy and thermal performance analysis. The majority of building performance simulators in the UK make use of CIBSE weather files as trusted consistently replicable weather data sets in their work, as it offers a single data set for a particular location, climatic period, emission scenario, and probability level for all designers to compare building performances [16,18]. This serves as the primary reason for the use of CIBSE weather data sets for this work.

This paper analyses the variability of the selected comparable CIBSE TM48 and CIBSE TM49 weather data set on internal operative temperatures to identify the most influential weather parameters that contribute to indoor operative temperatures in three locations in London. Uncertainty and sensitivity analysis of the CIBSE weather data sets based on the deterministic single projection of UKCIP02 and the CIBSE weather data sets based on the probabilistic UKCP09 projections is performed to ascertain the contrast between the two files. In addition, the 50th percentile central estimate weather files for Heathrow 1989 was used to provide comparable outputs in relation to the CIBSE's 2008 weather files. Moreover, the UKCP09 A1B (medium emission scenario) and the UKCIP02 A2 (medium-high emission scenario) are used for comparative analysis, as the two emission scenarios are closer in the chosen time period.

1.2. Monte Carlo Uncertainty and Sensitivity Analysis

The key to determining the target output of thermal comfort is a comprehensive building model and credible input variable information [19]. Though uncertainties of input variables may have significant implications on building simulations, they are quite often not identified, quantified, or included in building simulations [19]. Most simulation programs do not incorporate uncertainties in input and thus result in outputs of single estimates [19]. Uncertainties in building energy simulations are associated with the variability of the weather data, the thermo-physical properties of the buildings in relation to the building fabric and systems, and the associated internal heat gains coupled with variable occupant behaviour. The occurrence of uncertainties is attributed to incomplete specifications, inadequate knowledge of building characteristics, and a lack of specifications in operating conditions in relation to weather, internal heat gains, and system set points [19]. It may also relate to inherent simplifications of a model and a lack of sufficient input data information [20]. The impact of these input uncertainties influence the accuracy of building energy simulations in spite of the efficacy of the applied model [19]. Uncertainty analysis is thus used to determine a confidence limit for a model output [21].

1.3. Thermal Comfort

Thermal comfort is defined as that condition of mind that expresses satisfaction with the thermal environment [22]. It is one of the main criteria in accessing the overall post occupancy of building [23] and involves the interactions between the climate, the building with its services, and variable occupant behaviour [24]. Global thermal comfort models fall into two broad classes: the adaptive [25] and the rational [26]. Adaptive models are generally based on field investigations aimed to correlate acceptable indoor conditions as a function of the mean outdoor temperature [27]. On the contrary, the rational approach is based on the correlation of the thermal sensation with the heat balance equation on the human body [28], which is affected by the indoor microclimate (air temperature, mean radiant temperature, humidity, and air velocity) and personal parameters (activity and clothing thermophysical properties). For both approaches and under specific hypotheses in terms of the values of the main variables affecting the thermal sensation [26], the operative temperature can be used as an indicator of indoor comfort conditions.

Indoor operative temperature is a simplified measure of thermal comfort. Operative temperature can be calculated by averaging the air temperature with the mean radiant temperature with a weighting factor depending upon the air velocity [22]. Studies indicate that comfort temperature is closely related to the indoor operative temperature [29,30]. Too low or too high operative temperatures affect the thermal comfort of building occupants in general [31].

This paper focuses on using building simulation tools to produce indoor climatic data in the form of operative temperatures as a means of expressing thermal comfort based on CIBSE TM52 overheating criteria that is underpinned by the adaptive thermal comfort models. The CIBSE TM52 criteria is for naturally ventilated buildings [24].

2. Materials and Methods

In this work, Monte Carlo approaches are used in estimating climatic deterministic, uncertainty, and sensitivity analysis through a series of simulations using the UK Charted Institution of Building Services Engineers CIBSE UKCIP02 future weather years, CIBSE TM48 for design summer years (DSY), and the latest CIBSE TM49 DSY future weather data which incorporates the UKCP09 projections, to evaluate the variance in climatic projections and the impact of future climate change on the thermal comfort of a detached dwelling in the United Kingdom using the CIBSE TM52 overheating criteria. The global sensitivity analysis used in the study incorporates the standardised regression coefficient (SRC) and the partial correlation coefficient as sensitivity indices to identify the key parameters that contribute to thermal comfort implications in the dwellings due to climate change. In building simulation practices, it is acceptable for two different sensitivity analysis methods to be used to ascertain their robustness and further inspire confidence in the results [32].

The essence for the climatic sensitivity analysis is based on the following:

(1) the limitations of the CIBSE TM48 morphing methodology in producing certain variables that independently have no relationship to the probabilistic consideration of the UKCP09 CIBSE TM49 weather series, making the output different from the latest weather data series;
(2) differences in the baseline periods for the two climate projections: 1983–2004 and 1961–1990 baselines for the UKCIP02 and UKCP09 projections, respectively;
(3) a consideration of the London urban heat island effect in the CIBSE TM49 weather files leading to the generation of three different weather data sets for London; and
(4) a consideration of the extreme heat waves experienced in 1976 and 2003 years to examine overheating risk under different scenarios.

2.1. Thermal Analysis Simulation (TAS) 3D Modelling

It is generally recommended that for naturally ventilated buildings, the 50th percentile (best guess) projections and the medium greenhouse gas emission scenario has to be used in the building simulation analysis [33]. This choice of UKCP09 future weather file based on the 50th percentile of external temperature and 2050s emission scenarios was used because of its usage in other studies. For example, Mavrogianni et al. in 2012 used this criterion for their dynamic thermal simulation work for identifying factors that affect the high indoor summer temperatures in London dwellings [33]. The medium-high climate change emission scenario was chosen in the UPCIP02 weather file consideration. The CIBSE TM36, using dynamic thermal modelling, offered a quantitative assessment of the risks of overheating in 13 case study buildings comprising of houses, offices, and schools for three locations in the UK, using the UKCIP02 medium-high climate change scenario and the CIBSE Guide A (2006) [34] as the overheating criteria [35].

The various modelling and simulation parameters of Building Summary, Calendar, Building Elements, Zones, Internal conditions (which include thermostat set up, infiltration and ventilation, occupancy, lighting and equipment details), Schedule, and Aperture Types, which were used to populate and simulate each building, are maintained with the only variant being the weather data.

For details of the model, that is u-values, occupancy patterns, and other modelling and simulation assumptions and parameters, as well as the accuracy of the internal temperatures within the model, please see Appendix A.

A series of scenarios based on the current and the future climate variables on different timelines of 2020s, 2050s, and 2080s with their respective medium-high carbon scenarios for the CIBSE TM48 UKCIP02 weather files and similar time slice of 2020s, 2050s, and 2080s for CIBSE TM49 UKCP09 weather files are simulated for Gatwick Airport, London Weather Centre and Heathrow Airport.

2.2. Developing Multivariate Linear Regression

The case study is based on a building simulation and global sensitivity analysis that explores the analysis of uncertainties and sensitivities related to climate change variability. The IBM SPSS statistics Monte Carlo sensitivity analysis tool is used to identify the influential parameters that affect the internal operative temperature (thermal comfort) of dwellings.

The CIBSE weather data set used in the EDSL TAS simulation has seven key weather variables of global horizontal radiation, cloud cover, relative humidity, wind direction, wind speed, diffused horizontal radiation, and dry bulb temperature. Table 1 indicates the input parameters with their probability distributions for the uncertainty and sensitivity analysis for the climate change impact on thermal comfort. The CIBSE weather data sets used in this study are the design summer year (DSY) CIBSE TM48 UKCIP02 weather files and the CIBSE TM49 UKCP09 weather files for Gatwick Airport, London Weather Centre, and Heathrow Airport.

Table 1. Input parameters with their probability distributions for the uncertainty and sensitivity analysis for the climate change impact on thermal comfort.

Input Parameter	Acronym	Units	Probability Distribution
Global Radiation	GR	W/m^2	Normal
Diffused Radiation	DR	W/m^2	Normal
Cloud Cover	CC	(0–1)	Normal
External Temperature	ET	(°C)	Normal
External Humidity	EH	(%)	Normal
Wind Direction	WD	(°)	Normal
Wind Speed	WS	(m/s)	Normal
Average Radiation Temperature	ART	(°C)	Normal
Average Dry Bulb Temperature	ADBT	(°C)	Normal
Daily Hourly Exponentially Weighted Running Mean Temperature	DHEWRMT	(°C)	Normal

The detached dwelling used as the case study is 49 Carnation Drive, a 1995 three-bedroom house located at Bracknell, Berkshire, about 48 km from Central London, the closest weather station for CIBSE TM48 UKCIP02. For CIBSE TM49 UKCP09 weather files, the case study building location is located at 48.87 km, 48 km, and 18.71 km respectively from Gatwick Airport, London Weather Centre and Heathrow Airport.

EDSL TAS simulations were performed on variations of climate change as input parameters and consider uncertainties in various CIBSE DSY weather files in predicting indoor operative temperature as a thermal comfort indicative parameter. The EDSL TAS coupled with the developed Excel CIBSE TM52 overheating criteria historical data were then sent to IBM SPSS statistical software to create a multivariate linear regression XML model. The aim of this multivariate linear regression model was to capture the complex thermal interaction of parameters used in the EDSL TAS program. The uncertainty and sensitivity analysis on the multivariate linear regression model was then subsequently analysed using IBM SPSS statistics software.

2.3. Uncertainty and Sensitivity Analysis Due to Climate Change

This work employs the box and whiskers plot as one of the effective methods used in uncertainty analysis. The box and whiskers plot presents a summary of the important data set characteristics of the maximum and minimum values, the median, the dispersion, asymmetry, the extreme values, and the percentile rank analysis [36].

The purpose of sensitivity analysis in building performance modelling and simulation and observational study is to explore the uncertainty of the key input parameters that influence the prediction of the building performance parameters and to investigate the important varying contribution of different design parameters with respect to building performance [12,37]. The regression sensitivity analysis is mostly used in building performance analysis due to its computational and results interpretation simplicity [37].

The standardised regression coefficient (SRC) or the beta value method sensitivity analysis is widely used in the literature [12,37,38] and as it offers variability measure of independent input parameters in a linear regression model. The SRC offers a quantitative global sensitivity analysis index which is robust and easy to use [20]. It gives a quantitative measure of parameter sensitivity and influences the different input parameters on the output with the sign indicating the direction of the parameter sensitivity to the target parameter [38].

The standardised regression coefficient (SRC) and partial correlation coefficient (PCC) are chosen as regression sensitivity methods because they are appropriate for linear models [38]. The partial correlation assists in the examination of the relationship or association between two variables whilst controlling the other variables. Whilst the two methods may give the same results in the case of uncorrelated inputs, differences in results may show if there are correlated inputs as only PCC is appropriate for both correlated and uncorrelated inputs, but SRC is only suitable for uncorrelated inputs [38]. The standardised rank regression coefficient is not used, as it is only applicable for non-linear models [38].

Sensitivity analysis involves the changes in different design parameters to ascertain their relative influence on the target variable. The developed multivariate linear regression XML model is used to run the uncertainty and sensitivity analysis in the IBM SPSS statistical software. The Monte Carlo simulation was set to 100,000 iteration runs for each target parameter to provide adequate coverage of the solution space. The results of the uncertainty analysis are presented as box and whiskers plots. The box and whiskers plot also shows the variations in sensitivity measures for various input parameters. The IBM SPSS software is then used to calculate the standardised regression coefficient (SRC) and partial correlation coefficient (PCC) to ascertain the input parameters that are most sensitive and thus explain the high variability in the models.

3. Results

3.1. Deterministic Analysis

Figure 1 illustrates the deterministic analysis results in the form of histogram. The analysis compares the maximum, minimum, average, and range of internal operative temperatures using CIBSE TM52 as overheating criteria and of UKCIP02 Heathrow DSY medium-high and the UKCP09 Heathrow 1989 medium 50% probabilistic scenarios weather data sets.

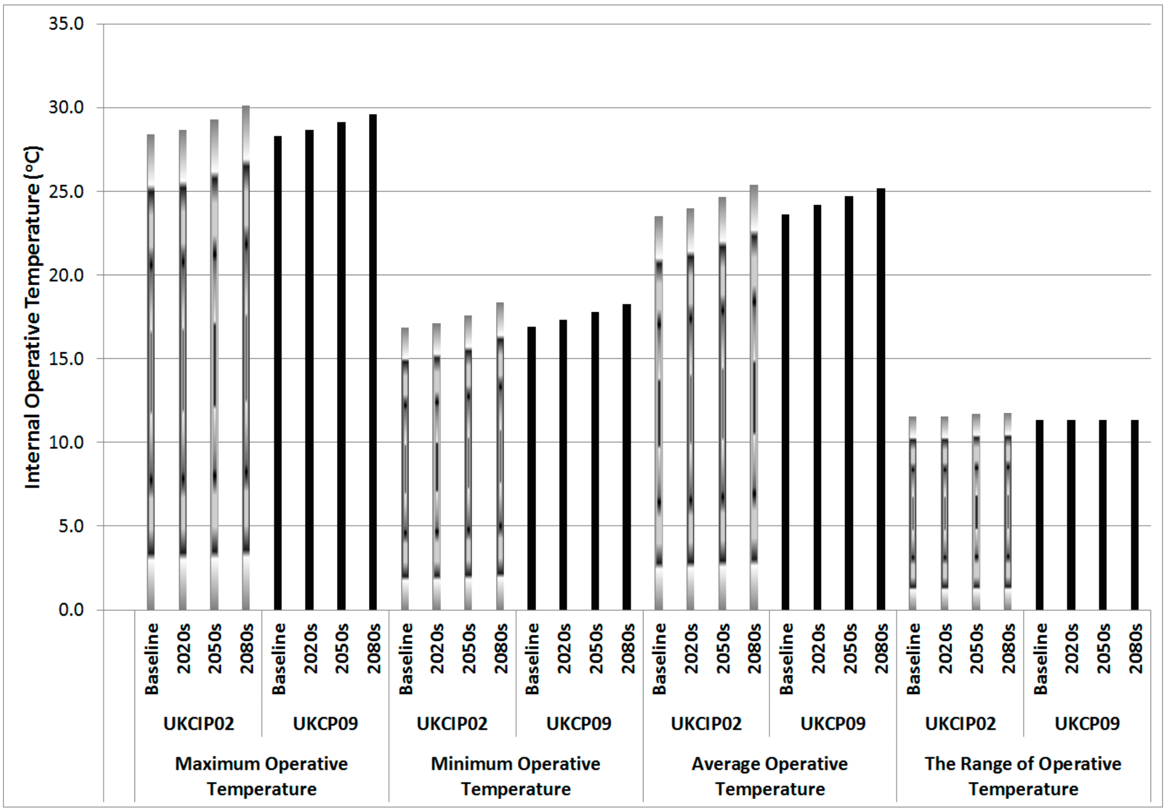

Figure 1. Internal operative temperatures for UKCIP02 Heathrow DSY medium-high and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios.

There is a marginal difference in maximum operative temperatures for the Heathrow DSY medium-high and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios for the baseline, 2020s, and 2050s weather data sets, with the former being slightly higher. For the 2080s scenarios, the difference in operative temperature for the two weather data sets is about 0.5 °C. The minimum operative temperature variability indicates a similar trend of marginal difference. The minimum operative temperatures for the UKCP09 Heathrow DSY 1989 medium 50% probabilistic scenarios' weather data sets for the baseline, the 2020s, and 2050s timelines show slightly higher temperatures in the range of about 0.1 °C for all respective comparative scenarios. The 2080s scenario variation is the opposite of that observed in other timelines with the UKCIP02 showing slightly higher minimum temperatures. The average internal operative temperatures for the two weather data sets' respective timelines show a strong similarity in the trend of average operative temperatures. The range operative temperatures for the UKCIP02 Heathrow DSY medium-high are slightly higher than their respective comparative timelines for the UKCP09 Heathrow 1989 medium 50% probabilistic scenarios, ranging from about 0.25 °C to 0.42 °C for the baseline and 2080s scenarios respectively.

Figures 2–5 illustrate the deterministic analysis results in the form of histogram analysis comparison of the maximum, minimum, average and range of operative temperatures of UKCP09 Heathrow DSY Medium 50% probabilistic scenarios for 1976, 1989 and 2003 and the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria.

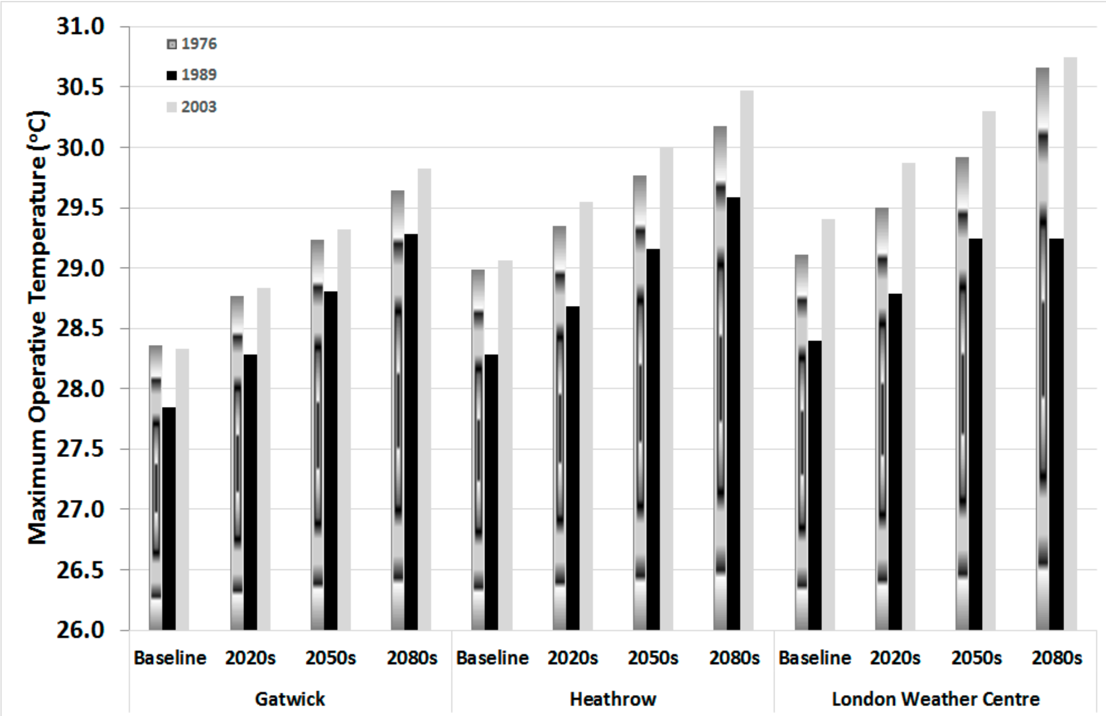

Figure 2. A comparison of maximum internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

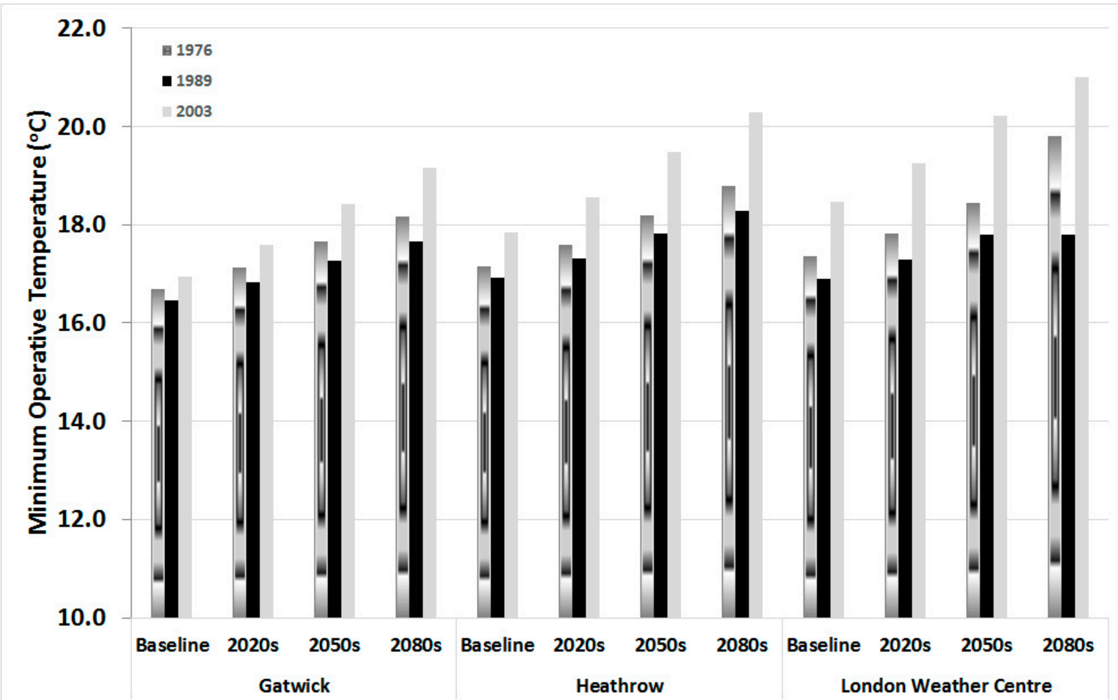

Figure 3. A comparison of minimum internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

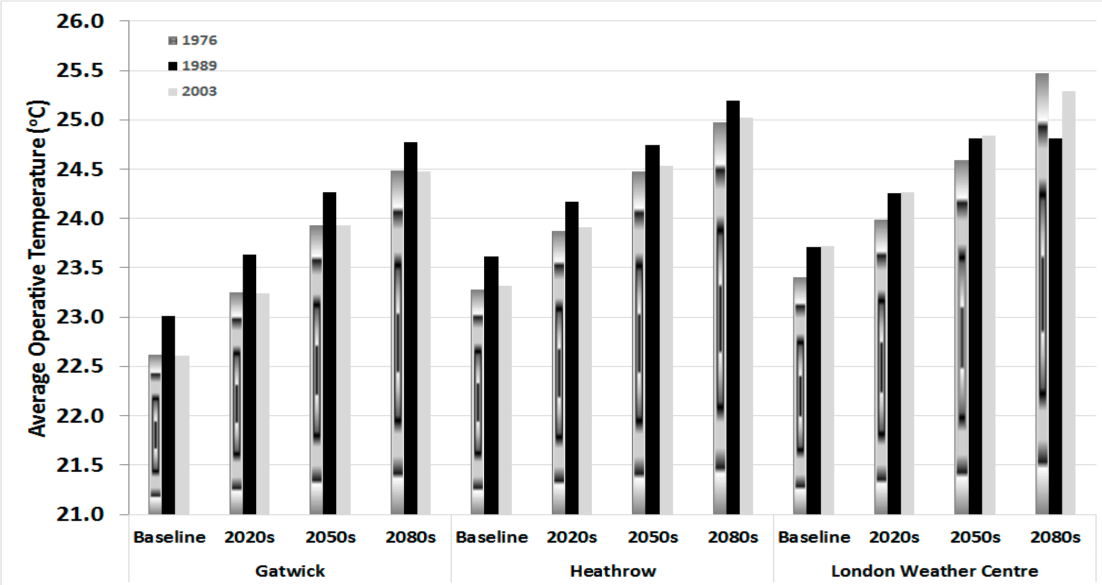

Figure 4. A comparison of average internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

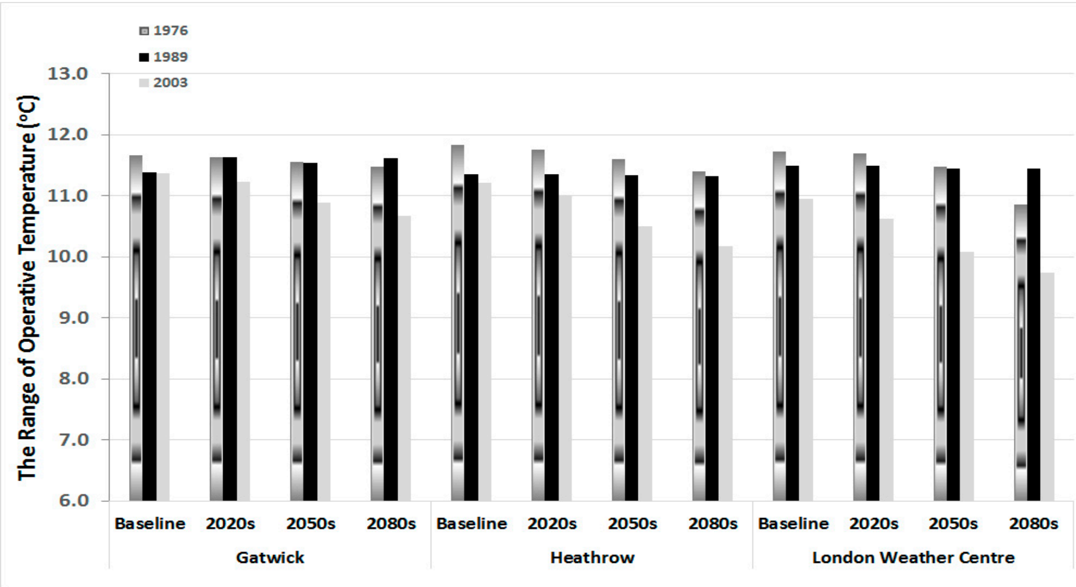

Figure 5. A comparison of the range internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

As expected, there is a progressive increase in maximum internal operative temperatures for 1976 and 2003 for all timeline scenarios. Gatwick has the lowest maximum operative temperatures whilst London Weather Centre is observed to have the highest operative temperatures. The difference in the maximum operative temperatures between the various timeline scenarios of Gatwick when compared with Heathrow and London Weather Centre show a difference of about 0.6 °C and 1.0 °C for Heathrow and London Weather Centre respectively. The highest maximum operative temperatures for the London Weather Centre timelines could be attributed to the urban heat island effect. Similar trends are observed in Figure 3 which compares the minimum internal operative temperatures for the three locations using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

The average operative temperatures for the three locations indicated as expected, with London Weather Centre having the highest average temperatures followed by Heathrow. Gatwick has the least average operative temperatures when compared to the other two locations. The 1989 medium 50% probabilistic weather data set appears to have slightly higher average operative temperatures of about 0.5 °C when compared to all scenarios of the 1976 and 2003 weather data sets. Comparison of the range operative temperatures shows the 2003 medium 50% probabilistic weather data set to have the lowest value when compared to the other years.

3.2. Uncertainty Analysis—Box and Whiskers Plots

Figure 6 illustrates the comparison of the UKCIP02 Heathrow DSY medium-high and UKCP09 Heathrow DSY 1989 medium 50% probabilistic weather data set effect on internal operative temperature to ascertain the impact of climate change on thermal comfort of residential buildings. The box and whiskers plot is a graphical method of representing data through their quartiles. The plots show the uncertainty associated with Monte Carlo simulation of overheating analysis with internal operative temperatures as the output parameter using the various weather scenarios indicated above as the only variants. The ten (10) input variables as displayed in Table 1 are used in the analysis and the same sample size of 3672 hourly data between 1 May and 30 September as specified in the CIBSE TM52 overheating criteria which were used in each analysis.

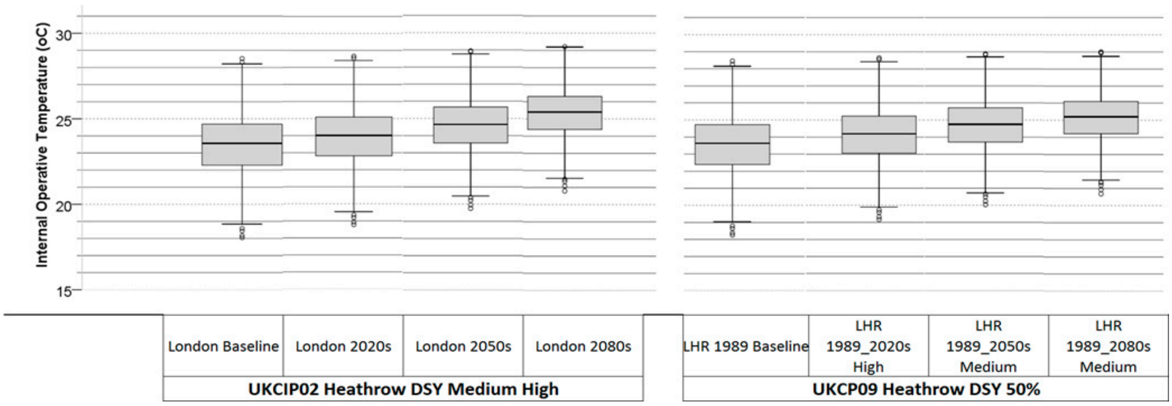

Figure 6. Box and whiskers plots of the UKCIP02 Heathrow DSY medium-high and UKCP09 Heathrow DSY 1989 medium 50% probabilistic weather data set.

A comparison of the median lines shows that the 50th percentiles of the UKCP09 for the 2020s and 2050s are slightly higher than that of the UKCIP02 weather projections, whilst the opposite is realised with regard to the 2080s weather data set. However, the overall pattern of variability of the two weather data sets seems to be not very different from each other as analysis of the UKCIP02 and UKCP09 results show that the median changes from 23.5 °C to 25.4 °C and 23.5 °C to 25.3°C respectively. Thus, there is no marked observable effect of change in internal operative temperatures in the two sets of the uncertainty analysis results.

The whiskers of the plots, indicated by the extended vertical lines above and below the plots and which show the variability of the internal operative temperatures outside the upper (75th percentiles) and lower quartiles (25th percentiles) to the 90th percentile and 10th percentile of the data sets respectively, also show symmetry pointing to the non-skewedness of the data. The whisker plots progressively decrease along the time lines of the two different weather data sets with the decrease in the UKCP09 Heathrow 1989 DSY Medium 50% probabilistic weather data sets slightly more pronounced than the UKCIP02 Heathrow DSY medium-high data sets.

The outliers showing the individual points outside the whiskers with 10% probability of occurrence are virtually similar when comparing the respective timeline scenarios of the two different weather data sets. The outliers for both the maximum and minimum values generally lie close to the whiskers' ends.

Figure 7 illustrates the box plots comparison of the internal operative temperatures reported in relation to the effect of the design summer year (DSY) medium 50% probabilistic scenarios of the 1976, 1989, and 2003 weather data sets of Gatwick, Heathrow, and London Weather Centre.

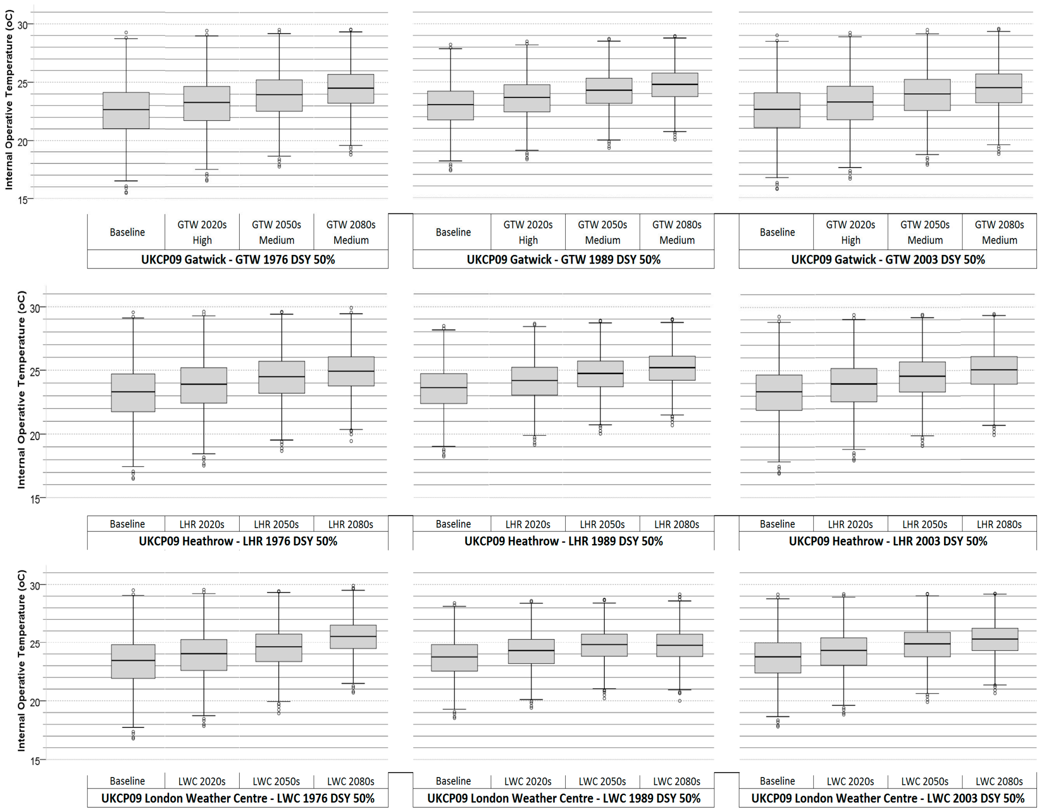

Figure 7. Box and whiskers plot comparison of the internal operative temperatures reported in relation to the effect of the design summer year (DSY) medium 50% probabilistic scenarios of the 1976, 1989, and 2003 weather data sets of Gatwick, Heathrow, and London Weather Centre.

In general, there is zero skewedness of the interquartile ranges and the whiskers. A progressive decrease of variability in the length of the interquartile ranges (IQR) is observed along the years, coupled with a progressive decrease in the whiskers. Thus, the baselines have larger dispersion for both the box and the whiskers and progressively decrease along the timelines.

Moreover, the variability of the interquartile range and the relative dispersion of the data set outer range are larger in the 1976 and 2003 scenarios than that of the 1989 scenario, indicating a clustering of parameters near the 25th and 75th percentiles and a further large dispersion of the outliers.

As expected, the medians of the 1989 scenarios of Gatwick, Heathrow, and London Weather Centre are comparatively lower than those of the 1976 and 2003 scenarios. In addition, the interquartile ranges and the whiskers are relatively smaller. This observation points to a relatively middle clustering of data about the medians, 25th percentiles, and the 75th percentiles of the 1989 timeline scenarios, indicating less uncertainty in the target variable of internal operative temperatures.

In general, the medians for the 2003 scenarios are higher than those of the 1976 scenarios. Furthermore, analysis of Figure 7 shows that the medians of the London Weather Centre timeline scenarios are higher than those of their comparative Heathrow timelines scenarios and even higher than those of the Gatwick timeline scenarios. This could be attributed to the urban heat effect in the city of London. As anticipated, the outliers of the 1976 and 2003 weather scenarios lie further away from the whiskers when compared with that of the 1989 data set point towards more extreme internal operative temperatures in those years' weather data sets.

3.3. Sensitivity Analysis with SRC and PCC as Sensitivity Indices

Figure 8 illustrates the comparison of the standardised regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCIP02 Heathrow and UKCP09 1989 Heathrow weather data sets. Figure 9 illustrates the comparison of the standardised regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCP09 1976 Gatwick, Heathrow and London Weather Centre weather data sets.

Figure 8. Comparison of the standardised regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCIP02 Heathrow and UKCP09 1989 Heathrow weather data sets.

All the sensitivity analysis results, when considering the variation of the weather data alone, indicate that the internal operative temperature of dwellings is mostly influenced by the radiant temperature and the dry bulb temperature. The other weather variables of wind direction, wind speed, external humidity, external temperature, cloud cover, diffused radiation, global radiation, and the daily hourly exponentially weight running mean temperature have a relatively small impact on the internal operative temperature. This observation is in consonance with the formulae used in predicting thermal comfort in CIBSE TM52 and BSI (2007) BS EN 15251, which combine the air and radiant temperatures to obtain the operative temperature.

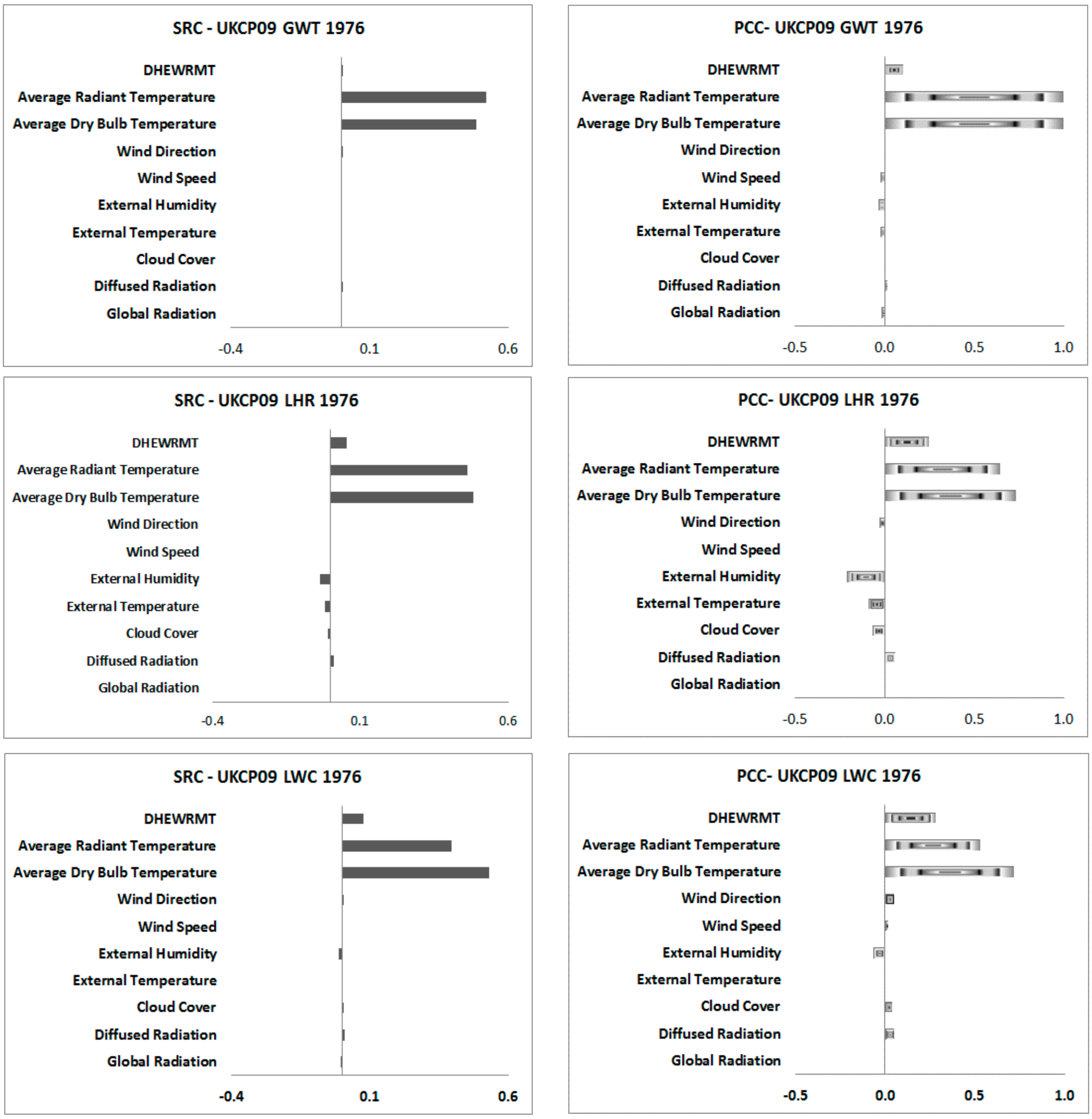

Figure 9. Comparison of the standardised regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCP09 1976 Gatwick, Heathrow and London Weather Centre weather data sets.

4. Discussion and Conclusions

This study investigated the impact of varying weather patterns on the thermal performance of dwellings. The work is underpinned by building simulation models in TAS coupled with the Monte Carlo global sensitivity analysis method using IBM SPSS to indicate that the proposed method can facilitate the analysis and prediction of sensitive weather parameters which influence the thermal comfort of residential buildings.

The deterministic analysis results of the UKCP09 Heathrow DSY Medium 50% probabilistic scenarios for 1976, 1989, and 2003 indicated a progressive increase in maximum internal operative temperatures for the 1976 and 2003 years for all timeline scenarios. Gatwick had the lowest maximum operative temperatures, whilst London Weather Centre was observed to have the highest operative temperatures. This affirmed the incorporation of the urban heat island effect of the London Weather Centre weather data sets of CIBSE TM49, as compared with the Heathrow and Gatwick weather files.

The Monte Carlo uncertainty analysis results of the median lines showed that the 50th percentiles of the UKCP09 for the 2020s and 2050s are slightly higher than that of the UKCIP02 weather projections, whilst the opposite is realised with regard to the 2080s weather data set. However, the overall patterns of variability of the two weather data sets do not seem to be very different from each other, as analysis of the UKCIP02 and UKCP09 results show that the median changes from 23.5 °C to 25.4 °C and 23.5 °C to 25.3 °C, respectively. Thus, there is no marked observable effect of change in internal operative temperatures in the two sets of the uncertainty analysis results. However, the deterministic results shows the operative temperatures of the UKCIP02 are slightly higher than those of UKCP09, with the UKCP09 having a narrow range of operative temperatures.

The Monte Carlo sensitivity analysis quantified and identified the dry bulb and radiant temperatures as the most influential weather parameters that affect thermal comfort on dwellings. This finding agrees with published literature (CIBSE TM52, 2013; CIBSE Guide A, 2006). These study results further indicate the marginal differences in maximum and minimum operative temperatures for the Heathrow DSY medium-high and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios for the baseline, 2020s, and 2050s weather data sets, with the former being slightly higher. For the 2080s scenarios, the difference in maximum operative temperature for the two weather data sets was about 0.5 °C. Moreover, the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria for the UKCIP02 Heathrow DSY medium-high and UKCP09 Heathrow DSY 1989 medium 50% probabilistic scenario weather data sets showed a very strong similarity in the respective timelines for the two weather data sets.

The standardised regression coefficient and the partial correlation coefficients are useful sensitivity indices for determining the relative importance of weather parameters that influence the indoor operative temperatures of dwellings. The work stresses the need for climate sensitive design, and knowledge of this could offer insight for efficient designs and retrofitting practice to improve the thermal comfort of dwellings. In addition, this work is useful in sustainable engineering practice, as it could be extended to the energy requirements of buildings.

For easy analysis and replicable of the methodology used in this work, it is recommended that building simulation software incorporate Monte Carlo and global sensitivity analysis as key standard functionalities of its modelling. This will enable simulation software to facilitate the analysis and predict key thermal performance parameters and further assess different energy conservation measures.

Author Contributions: Ali B-Jahromi conceived and designed the project; Joseph Amoako-Attah performed the experiments and analyzed the data. Joseph Amoako-Attah and Ali B-Jahromi wrote and reviewed the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Modelling and Simulation Parameters and Assumptions.

Building Fabric—Calculated area weighted average U-values	Wall	0.42 W/m^{2}K
	Floor	0.46 W/m^{2}K
	Roof	0.19 W/m^{2}K
	Windows	3.29 W/m^{2}K
	Door	2.74 W/m^{2}K
	Garage door	1.77 W/m^{2}K
Construction Data Base	NCM Construction—v5.2.tcd	
Occupancy levels; People density; Lux level	Bath	0.01873684 pers/m^2. 150 Lux
	Bed	0.01873684 pers/m^2. 100 Lux
	Circulation area	0.02293877 pers/m^2. 100 Lux
	Dining	0.0169163 pers/m^2. 150 Lux
	Kitchen	0.0237037 pers/m^2. 300 Lux
	Lounge	0.0187563 pers/m^2. 150 Lux
	Toilet	0.02431718 pers/m^2. 100 Lux
Fuel Source	Natural Gas	CO_2 Factor 0.216 Kg/kWh
	Grid Electricity	CO_2 Factor 0.519 Kg/kWh
Orientation	Latitude, longitude and time zone used in the modelling are 51.5 degrees North 0.4 degree East and UTC + 0.0 respectively to reflect the geographical and time parameters of London. Sheppey, Sheerness is 59.4 km from London, the closest weather station.	
Glazing	4-16-4 uncoated glass, air filled; solar energy transmittance of 0.76 and total (normal) light transmittance of 0.8	
Ventilation	Simple natural cross-ventilation in all directions. Window width is 10% less than wall external area. Openable window proportion 50% set in the manner of side openable windows. Set openable window temperature 20–21 °C (control zone dry bulb temperature). Openable window schedule 8 a.m. to 4 p.m.	
Weather data	DSY (CIBSE) for Gatwick, Heathrow and London Weather Centre. It includes Global Solar Radiation, Diffuse Solar Radiation, Cloud Cover, Dry Bulb temperature, Relative Humidity, Wind Speed and Wind Direction.	
Impact of shading	TAS simulation of "mean height of surroundings"	
Terrain type	City	
Ground reflectance	TAS default value of 0.2	
Calendar	NCM Standard	
Air Permeability	10 m^3/hm^2@50Pa	
Infiltration	0.500 ACH	
Lighting Efficiency	5.2 W/m^2 per 100 lux	
Average Conductance	172 W/K	

References

1. Palme, M.; Isalgue, A.; Coch, H. Avoiding the Possible Impact of Climate Change on the Built Environment: The Importance of the Building's Energy Robustness. *Buildings* **2013**, *3*, 191–204. [CrossRef]
2. Amoako-Attah, J.; B-Jahromi, A. Impact of Conservatory as passive solar design of UK dwellings. *Proc. Inst. Civ. Eng. J. Eng. Sustain.* **2016**, *169*, 198–213. [CrossRef]
3. Amoako-Attah, J.; B-Jahromi, A. Method comparison analysis of dwellings' temperatures in the UK. *Proc. Inst. Civ. Eng. J. Eng. Sustain.* **2015**, *168*, 16–27. [CrossRef]
4. Amoako-Attah, J.; B-Jahromi, A. Impact of standard construction specification on thermal comfort in UK dwellings. *Adv. Environ. Res.* **2014**, *3*, 253–281. [CrossRef]

5. Amoako-Attah, J.; B-Jahromi, A. Impact of future climate change on UK building performance. *Adv. Environ. Res.* **2013**, *2*, 203–227. [CrossRef]
6. Hulme, M.; Jenkins, G.L.; Lu, X.; Turnpenny, J.R.; Mitchell, T.D.; Jones, R.G.; Lowe, J.; Murphy, J.M.; Hassel, D.; Boorman, P.; et al. *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*; Tyndall Centre for Climate Change Research, University of East Anglia: Norwich, UK, 2002.
7. Jenkins, G.J.; Murphy, J.M.; Sexton, D.M.H.; Lowe, J.A.; Jones, P.; Kilsby, C.G. *UK Climate Projections: Briefing Report*; Met Office Hadley Centre: Exeter, UK, 2009.
8. The Chartered Institution of Building Services Engineers. *The Use of Climate Change Scenarios for Building Simulation: The CIBSE Future Weather Years*; CIBSE TM48; Chartered Institution of Building Services Engineers: London, UK, 2008.
9. Williams, D.; Elghali, L.; France, C.; Wheeler, R.C. Projecting building energy demand using probabilistic weather conditions accounting for climate change. In Proceedings of the CIBSE Technical Symposium, DeMontfort University, Leicester, UK, 6–7 September 2011.
10. Belcher, S.E.; Hacker, J.N.; Powell, D.S. Constructing design weather for future climates. *Build. Serv. Eng. Res. Technol.* **2005**, *26*, 49–61. [CrossRef]
11. Mylona, A. The use of UKCP09 to produce weather files for building simulation. *Build. Serv. Eng. Res. Technol.* **2012**, *33*, 51–62. [CrossRef]
12. Tian, W.; de Wilde, P. Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: A UK case study. *Autom. Constr.* **2011**, *20*, 1096–1109. [CrossRef]
13. Eames, M.; Kershaw, T.; Coley, D. On the creation of future probabilistic design weather years from UKCP09. *Build. Serv. Eng. Res. Technol.* **2011**, *32*, 127–142. [CrossRef]
14. The Chartered Institution of Building Services Engineers. *Design Summer Years for London*; CIBSE TM49; Chartered Institution of Building Services Engineers: London, UK, 2009.
15. Virk, G.; Mylona, A.; Mavrogianni, A.; Davies, M. Using the new CIBSE design summer years to assess overheating in London: Effect of the urban heat island on design. *Build. Serv. Eng. Res. Technol.* **2015**, *36*, 115–128. [CrossRef]
16. Gupta, R.; Gregg, M.; Du, H.; Williams, K. Evaluative application of UKCP09-based downscaled future years to simulate overheating risk in typical English homes. Structural Survey. *Struct. Surv.* **2013**, *32*, 231–252. [CrossRef]
17. Smith, S.T.; Hanby, V.I. Methodologies for the generation of design summer years for building energy simulation using UKCP09 probabilistic climate projections. *Build. Serv. Eng. Res. Technol.* **2012**, *33*, 9–17. [CrossRef]
18. Watkins, R.; Levermore, G.J.; Parkinson, J.B. Constructing a future weather file for use in building simulation using UKCP09 projections. *Build. Serv. Eng. Res. Technol.* **2011**, *32*, 293–299. [CrossRef]
19. Dominguez-Munoz, F.; Cejudo-Lopez, J.M.; Carrillo-Andres, A. Uncertainty in peak cooling load calculations. *Energy Build.* **2010**, *42*, 1010–1018. [CrossRef]
20. Rodriguez, G.C.; Carrillo-Andres, A.; Dominguez-Munoz, F.; Cejudo-Lopez, J.M.; Zhang, Y. Uncertainties and sensitivity analysis in building energy simulation using macroparameters. *Energy Build.* **2013**, *67*, 79–87. [CrossRef]
21. Spitz, C.; Mora, L.; Wurtz, E.; Jay, A. Practical application of uncertainty and sensitivity analysis in building energy simulation using macro parameters. *Energy Build.* **2012**, *67*, 79–87.
22. Handbook, A.F. Thermal Environmental Conditions for Human Occupancy, ASHRAE Standard 55-2010. In *American Society of Heating, Refrigerating and Air-Conditioning Engineers*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2009.
23. De Dear, R.J.; Akimoto, T.; Arens, E.A.; Brager, G.; Candido, C.; Cheong, K.W.D.; Li, B.; Nishihara, N.; Sekhar, S.C.; Tanabe, S.; et al. Progress in thermal comfort research over the last twenty years. *Indoor Air* **2013**, *23*, 442–461. [CrossRef] [PubMed]
24. The Chartered Institution of Building Services Engineers. *The Limits of Thermal Comfort: Avoiding Overheating in European Buildings CIBSE TM52*; Chartered Institution of Building Services Engineers: London, UK, 2013.
25. Nicol, F.; Humphreys, M.; Roaf, S. *Adaptive Thermal Comfort: Principles and Practice*; Routledge: London, UK, 2012.
26. D'Ambrosio Alfano, F.R.; Olesen, B.W.; Palella, B.I.; Riccio, G. Thermal comfort: Design and assessment for energy saving. *Energy Build.* **2014**, *81*, 326–336. [CrossRef]

27. De Dear, R.J.; Brager, G.S. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans.* **1998**, *104*, 145–167.
28. Fanger, P.O. Calculation of thermal comfort: Introduction of a basic comfort equation. *ASHRAE Trans.* **1967**, *73*, 1–20.
29. Nicol, J.F.; Raja, I.A.; Allaudin, A.; Jamy, G.N. Climatic variations in comfort temperatures: The Pakistan projects. *Energy Build.* **1999**, *30*, 261–279. [CrossRef]
30. McCartney, K.J.; Nicol, F. Developing an adapting comfort algorithm for Europe; results of the SCATS project. *Energy Build.* **2002**, *34*, 623–635. [CrossRef]
31. Ponni, M.; Baskar, R. A study of comfort temperature and thermal efficiency of buildings. *Int. J. Eng. Technol.* **2015**, *7*, 1469–1477.
32. Tian, W. A review of sensitivity analysis methods in building energy analysis. *Renew. Sustain. Energy Rev.* **2013**, *20*, 411–419. [CrossRef]
33. Mavrogianni, A.; Wilkinson, P.; Davies, M.; Biddulph, P.; Oikonomou, E. Building Characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. *Build. Environ.* **2012**, *55*, 117–130. [CrossRef]
34. The Chartered Institution of Building Services Engineers. *CIBSE Guide A—Environmental Design*; Chartered Institution of Building Services Engineers: London, UK, 2006.
35. The Chartered Institution of Building Services Engineers. *Climate Change and the Indoor Environment: Impacts and Adaptation CIBSE TM36*; Chartered Institution of Building Services Engineers: London, UK, 2005.
36. Banacos, P.C. Box and Whiskers Plots for Local Climate Datasets: Interpretation and Creation Using Excel 2007/2010. Available online: http://www.weather.gov/media/erh/ta2011-01.pdf (accessed on 30 September 2016).
37. Storlie, C.B.; Swiler, L.P.; Helton, J.C.; Sallaberry, C.J. Implementation and evaluation of non-parametric regression procedures for sensitivity analysis computationally demanding modules. *Reliab. Eng. Syst. Saf.* **2009**, *94*, 1735–1763. [CrossRef]
38. Hygh, J.S.; DeCarolis, J.F.; Hill, D.B.; Ranji Ranjithan, S. Multivariate regression as an energy assessment tool in early building design. *Build. Environ.* **2012**, *57*, 165–175. [CrossRef]