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Improved Weather Files for Building Simulation

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Executive Summary

This work contributes to Objective 2 of the Demonstration of Energy Efficiency Potential (DEEP) research project, “To improve the accuracy of inputs to building simulation models to enable confidence in outputs”. Specifically, this report focuses on improving the weather data that is used for simulating buildings to understand energy demands, overheating risk, and moisture risks.

Weather data (in the form of weather files that contain observations of variables such as air temperature, wind speed and direction, and solar radiation) provide the boundary conditions in building simulations.

Currently, in the UK:

- Test Reference Years (TRYs) that depict average weather conditions are used for energy demand modelling. TRYs are compiled from individual months with the most average months to be chosen primarily based on air temperature, relative humidity, solar radiation and secondarily on wind speed.
- Design Summer Years (DSYs) are used to test a building at near-extreme conditions in terms of overheating. The DSY depicts a moderately hot year; the year for which only 1 in 7 summers (1984-2013) were hotter. In addition, a building can be assessed under more adverse conditions using DSYs files that depict an intense year and a long year. The intense year contains a warm spell with a duration similar to that of the moderate year but of higher intensity. The long year contains a warm spell with a greater duration and intensity of that of the moderate year, but its intensity is lower than that of the intense year.

There are limitations with this current approach, including:

- They ignore the inherent variability of the weather which may be required to facilitate decision-making.
- Different weather files are used for different applications such that the results may be inconsistent.

This report recommends that a single weather file for all types of building simulations should be used, to overcome these difficulties and to facilitate the simultaneous assessment of energy, overheating and hygrothermal performance of a building. This weather file, called hereafter Recent Weather Decade (RWD), includes year by year weather data for ten years (2010-2019) instead of just one representative year of weather; therefore, it picks up annual variation. Future weather files can then be obtained by morphing the RWDs using existing techniques.

This report describes the methods required to construct these files and gives guidance on how to present the results from ten years of simulation.

To demonstrate the improved approach, a case study building was assessed using RWD files for London, Manchester, and Glasgow. The results were compared with those from the TRY for the annual space heating energy demand and the DSY for the overheating assessment. A

two-bedroom, mid-floor, flat, with a south orientation, served as the case study building. It was chosen as a simple example and because flats can be prone to overheating.

For the London RWD, heating energy demand varied year on year: from 2701 kWh per annum to 4437 kWh per annum. The mean annual value was 11% higher than that obtained by using the London TRY. The RWD is a better approach to understanding average energy demands over years of fluctuating weather, as well as how the energy demands change from year to year. Heating energy demand results can be displayed as the 5%, 50% and 95% percentiles[1] based on the ten results from using the RWD, as shown in the figure below.

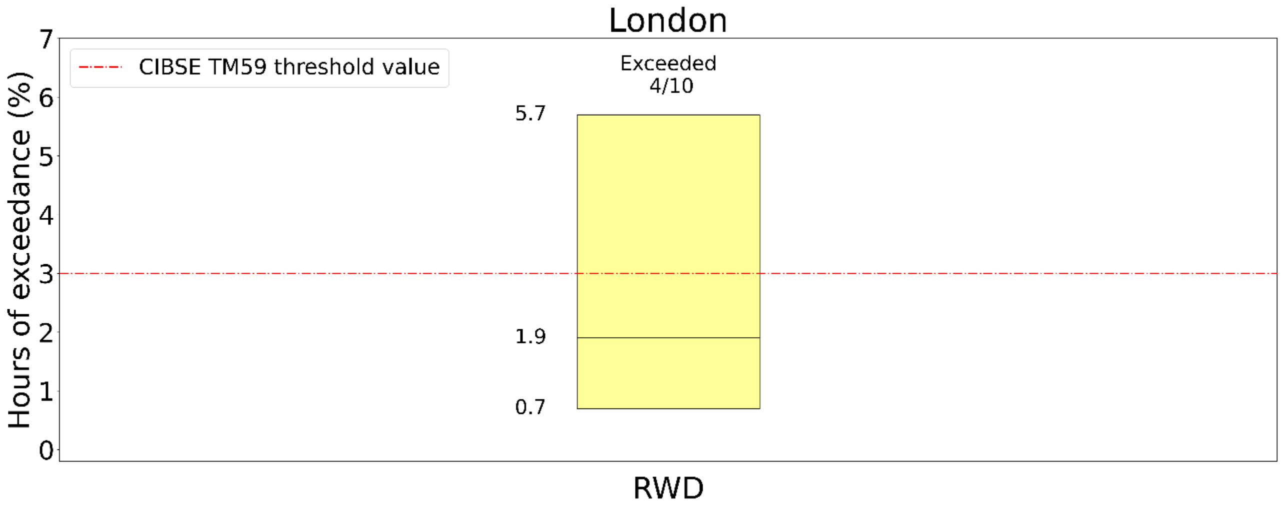
Annual space heating energy demand

For overheating, the London DSY predicted overheating in the living room while the RWD showed a pattern of overheating that varied from year to year predicting overheating in four out of the ten assessed years. The RWD is, therefore, a better approach to understanding the degree of overheating in different rooms and over years of fluctuating weather. This is because the assessment includes a range of weather with some cooler and some warmer summers, rather than just one year with a pass or fail outcome. If a room failed every year, it would be a greater concern than one that failed just one year.

Overheating hours of exceedance can be displayed as the 5%, 50% and 95% percentiles of the ten results from using the RWD, along with the number of years that the overheating assessment failed, as shown below.

[1] The percentiles are computed using linear interpolation. The 5 and 95% are used in order to exclude the extreme values within the RWD; the intention is to show how a building performs under near-extreme conditions.

TM59 criterion (% of occupied hours)

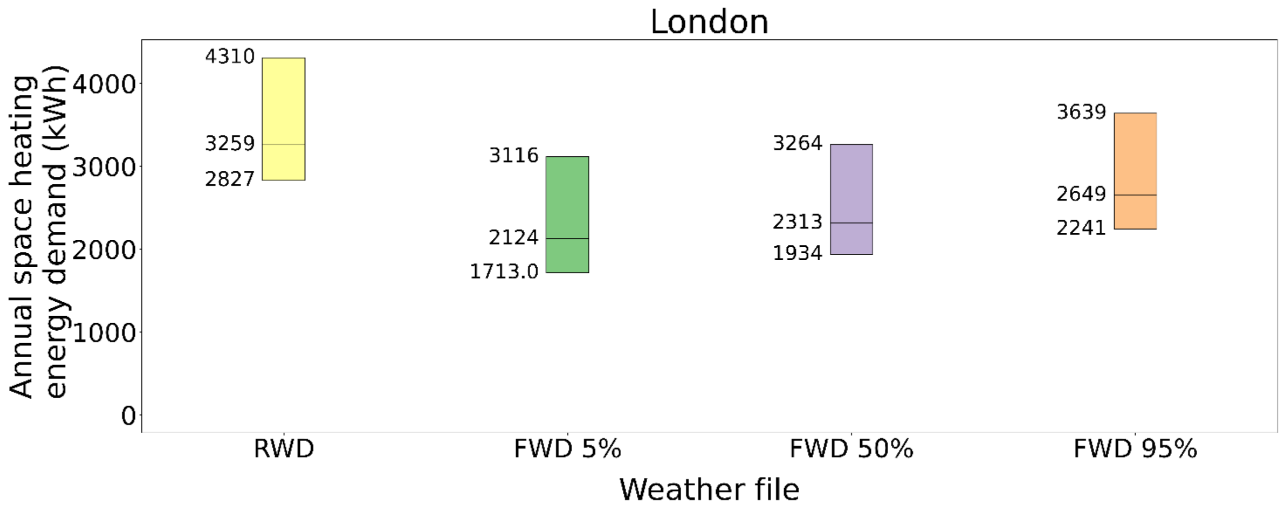


The use of RWDs will also be appropriate to hygrothermal modelling to understand moisture risk. Hygrothermal models are typically run for many years, as moisture transport in buildings is slow compared with heat transfer. A real decade of weather is arguably preferable to repeating a single year – the real variability is maintained, rather than repeating a particularly wet year, for example. Long term changes in patterns of rainfall are captured by using the most recent decade of weather.

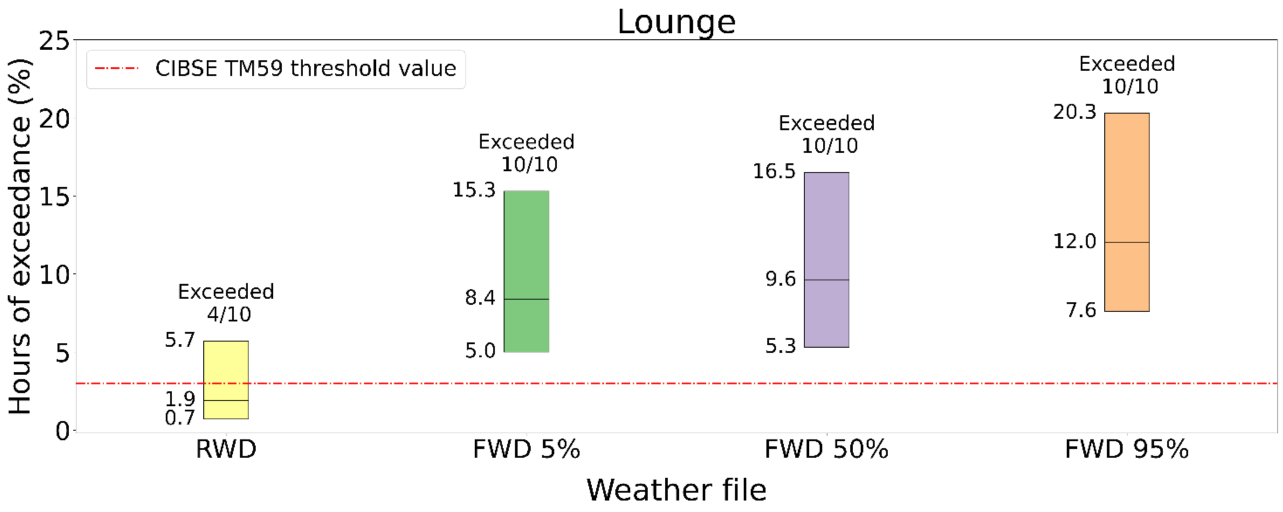
Morphing each of ten years of weather data in the RWD to create future weather decade (FWD) scenarios (each with 10 years of weather) using climate projections for the period 2051-2070 is relatively straightforward and preserves the relationship to today's weather. There are various climate projections available that account for the overall uncertainty, but here we focus on a low (5%), medium (50%), and high (95%) scenarios. The use of the 5th, 50th and 95th percentile results, calculated in the same way as for the RWD and each based on a morphed decade of weather data, helps illustrate the range of potential outcomes.

Examples for how the results from using a RWD and a FWD are shown below, for annual space heat energy demand and for overheating assessment.

Annual space heating energy demand



TM59 criterion (% of occupied hours)



Overall, the use of the RWD better captures the uncertainty in modelling that results from the natural variability in the weather. This benefit is also realised when the RWD is morphed to produce future weather decade (FWD) files.

Future work to develop the RWD files could consider the use of solar data from alternative sources (e.g., from the Copernicus Atmosphere Monitoring Service (CAMS) radiation service [1]), and whether leap years should be included or not. For the FWD files, different or additional time periods[2] could be considered. For both RWD files and FWD files, the representation of the Urban Heat Island (UHI) should be explored as this may be important for overheating assessment and is not fully represented in the weather observations.

[2] In this work, for the construction of the FWD files, the time period between 2051 to 2070 was considered.

1. Introduction

This report describes work carried out for the Department for Energy Security and Net-Zero (DESNZ) under their Demonstration of Energy Efficiency Potential (DEEP) research project. This work contributes to Objective 2, as stated in the invitation to tender (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/837866/Invitation-to-Tender-for-Demonstration-of-Energy-Efficiency-Potential-DEEP.pdf): “To improve the accuracy of inputs to building simulation models to enable confidence in outputs”. Specifically, this report focuses on improving the weather data that is used for simulating buildings to understand energy demands, overheating risk, and moisture risks. These data will be used in the DEEP project to assess energy retrofit measures.

The report considers the current state of the art in weather files (Section 2), presents the improved approach that has been developed for this research project and compares the results of using this new approach with the incumbent methods (Section 3), shows how the improved approach can be used to generate future weather files (Section 4), and provides examples of how the results from using this new approach can be presented (Section 5), before discussing the outcome and drawing conclusions (Section 6).

2. Current weather files

Weather data (in the form of weather files that contain observations of variables such as air temperature, wind speed and direction, solar radiation, etc.) provide the boundary conditions in building simulations. Ideally, these data should be collected close to the building of interest to reflect the microclimate but in most cases, they are obtained from weather stations located in airports that reflect the mesoclimate. The subsequent subsections provide insights into how a weather file is constructed with regards to the type of the building simulation application considered (e.g., overheating).

2.1. Energy demand

Currently, in the UK, Test Reference Years (TRYs) that depict average weather conditions are used for energy demand modelling [2]. TRYs are compiled from individual months with the most average months to be chosen primarily based on air temperature, relative humidity, solar radiation and secondarily on wind speed [3]. This process is performed using the Finkelstein-Schafer (FS) statistic method. In this method, the cumulative distribution for a specific weather parameter and a specific month is calculated and then it is compared against the cumulative distribution for the same weather parameter and month considering this time all the years included in the baseline period [4].

Other known weather files that are used worldwide for energy demand modelling include, among others, the Typical Meteorological Year (TMY) and the International Weather for Energy Calculations (IWEC). Although all of them represent average weather conditions, differences exist regarding the base time period used, the weather parameters considered as well as the weighting factors applied to them [5].

Overall, TRYs are found to be reliable when used in building simulations to predict the average energy demands of various building types including houses, schools and offices [3]. Nevertheless, it has been argued that buildings should be tested in addition under extreme conditions. In this way, the inherent variability of the climate is captured, and a range of energy use values is provided facilitating decision-making [6]. One other limitation of these weather files is that the Cloud Radiation Model (CRM) is used to derive the irradiance components; a model that it has been shown that doesn’t perform satisfactorily [7].

2.2. Overheating risk

In the UK, Design Summer Year (DSYs) are used to test a building at near-extreme conditions in terms of overheating [4]. In contrast to TRYs, a whole year of hourly weather observations are selected for a DSY. Firstly, the Static Weighted Cooling Degree Hours (SWCDH) are calculated for each of the years included in the dataset using Equation 1. Then, the year with the return period nearest to seven years[3] is selected as the DSY [8].

$$\text{SWCDH} = \sum_{all\ hours}(T_{outdoor} - T_{threshold})^2 \qquad \text{Equation 1}$$

where,

$T_{outdoor}$ is the outdoor air temperature

$T_{threshold}$ is a regional threshold temperature (Table 2, Eames, 2016)

Therefore, the DSY depicts a moderately hot year but the impact of the duration or intensity of warm spells[4] is not taken into account. For this reason, two more files are provided; an intense year and a long year. The intense year contains a warm spell with a duration similar to that of the moderate year but of higher intensity. The long year contains a warm spell with a greater duration and intensity of that of the moderate year, but its intensity is lower than that of the intense year.

The main advantages of the DSYs are that these files are based on actual weather data, the duration and intensity of warm events are taken into account, and that the process of compiling them is simple. Nonetheless, DSYs are constructed considering only air temperature and solar radiation is totally ignored. Furthermore, only the summer period (i.e. June to September inclusive) is considered; hence, hot weather outside this period which can have an impact on the overheating related performance of a building is also ignored (Jentsch et al., 2014). For example, high indoor temperatures exceeding 30°C have been recorded in flats located in London during October [10–12]. In the construction of the DSY for London, the limitations of the CRM are acknowledged, and it was decided to use monitored values of solar irradiation (global and diffuse) when these were available. For the cases that monitored data did not exist, values of diffuse irradiation were calculated. For the cases that monitored data existed but with gaps, these were filled through interpolation [13]. For the UK locations other than London it was not specified how the solar irradiation values were been obtained [8].

Jentsch et al. (2015) proposed an alternative way of constructing a weather file adequate for assessing the performance of a building under warm conditions. In this attempt the Summer Reference Year (SRY) is constructed by adjusting mathematically the TRY (through mathematical transformation: shifting, stretching, or a combination of the two) for the months April to September inclusive. In this way, a consistency is achieved between these two weather files. The main disadvantage of this approach is that the correlation between the weather parameters in the actual weather is not persevered since the weather parameters are adjusted individually. In addition, as it was mentioned earlier, warm weather that can occur outside the April to September period is not considered.

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[3] For example, if there were 21 years of weather data then the year with the 3rd highest SWCDH would have a return period of 7 years i.e. any other summer has a 1 in 7 chance of being hotter.

[4] A warm spell is defined as the continuous period where $T_{threshold}$ is exceeded for at least one hour of each day; warms spells that are separated by up three days are considered as the same event [8].

2.3. Moisture risks

In the UK, the standard that is associated with dynamic hygrothermal simulations, for modelling moisture risk, is BS EN 15026:2007 [15]. According to this British Standard [16], there are three possible options regarding the weather files that should be used (arranged from the most to least favourable):

1. A weather file that contains actual data and spans at least ten years.
2. A Reference Year that represents severe conditions (conditions that occur once every ten years).
3. A weather file in which the mean temperature has altered by ± 2°C (depending on whether the winter or summer period is more critical) whilst relative humidity remains unmodified.

While many modellers use Test Reference Years (TRYs – see section 2.1) for hygrothermal simulation, it is generally acknowledged that a TRY is inappropriate for hygrothermal simulations; moisture related damage is caused by sudden or rapid changes that occur in many weather parameters simultaneously which are not represented in TRYs [17]. For this reason, it might be preferable to test the hygrothermal performance of a building at near-extreme conditions as in the case of overheating. Hence, the development of a Design Moisture Year (DMY) is deemed to be necessary for the assessment of the hygrothermal performance of a building. In such a file, if moisture damage due to precipitation is expected, hourly rainfall data and coincident wind speed and direction (in order to model the impact of wind driven rain) should be included as well [18].

Nonetheless, the process of constructing such a file is complex and has to take into account whether winter or summer conditions are likely to cause more severe moisture damage, and which weather parameters should be included in this process. A difficulty that arises is that this process cannot be generalised since it depends highly on the characteristics of the investigated building. Moreover, it has been found that the impact of employing such a weather file instead of using a weather file constructed solely on air temperature is negligible on the outcome of a hygrothermal simulation [16]. For the above reasons it has been proposed that the hygrothermal performance of a building could be assessed using three different weather files depicting average, extreme hot and extreme cold weather [19].

3. Improved approach – Recent Weather Decade (RWD) files

3.1. Constructing Recent Weather Decade files

Weather conditions can alter greatly from year to year; this variation can result in fluctuations in the heating energy demand of a building. For example, for the USA, the Earth Gauge Report argues that a 0.9°C rise in average temperature can cause a decline in space heating energy demand of homes between 6 and 10% [20]. Nevertheless, the use of single year weather files has prevailed in the domain of building simulations [21]. In Section 2 it was shown how representative single years are currently constructed for different applications (energy, overheating and hygrothermal modelling). Such an approach impedes the objective evaluation of the performance of a building when energy use, overheating and moisture risk are considered simultaneously, for two reasons. First, because the criteria used to develop these files vary from application to application. Second, because the complexity and variability of actual weather is difficult to be capture in a single representative year.

To overcome these difficulties and to facilitate the simultaneous assessment of energy, overheating and hygrothermal performance of a building it is proposed that a single weather file for all types of building simulations should be used. Since it is argued that a period of ten years[5] is sufficient for the evaluation of the long-term performance of a building [16,21], this new weather file (named Recent Weather Decade (RWD) hereafter) contains data for the previous ten years (2010-2019).

An EnergyPlus weather file (epw) contains the following data: dry bulb temperature (°C), dew point temperature (°C), relative humidity (%), atmospheric station pressure (Pa), horizontal infrared radiation intensity (Wh/m^2), direct normal radiation (Wh/m^2), diffuse horizontal radiation (Wh/m^2), wind direction (degrees), wind speed (m/s) and total sky cover (tenths of coverage) [22]. For a hygrothermal assessment, as discussed earlier in Section 2.3, rainfall data are needed as well. The RWD file contains ten years of hourly values for all these parameters as derived from the ERA5 database (described below, Hersbach et al., 2018) through the Shiny weather data[6] application.

ERA5 is the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate where various climatic parameters are available at a spatial resolution of 0.25° x 0.25°[7] from 1979 to present. The climate reanalysis uses a weather model that combines and processes past weather observations (from weather stations

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[5] Although the reason is not explicitly described in these references, it is believed that ten years are considered enough to capture the variability in weather.

[6] The application can be found at https://shinyweatherdata.com.

[7] For London, this is approximately equal to 27.6 km x 17.3 km. Distance between degrees of latitude varies little with location, but a degree of longitude varies roughly from 111.3 km at the equator to zero km at the poles.

and satellites for example) to deliver in a consistent way a global picture of the past weather that matches reality to a great extent [23]. Therefore, a weather file can be constructed with no gaps for every location in the UK. This is the main reason that the ERA5 database was preferred over other databases (such as the MIDAS database) where very few complete years exist.

The diffuse horizontal radiation (DIF) and direct normal radiation (DNR) were calculated for the RWD using Equations 2 and 3. The direct horizontal solar radiation (DIR) and the global horizontal radiation (GHR) (which contains both direct and diffuse solar radiation) are retrieved directly from the ERA5 database. The solar altitude angle ($solar_{alt}$) is the angle between the sun's rays and a horizontal plane and was calculated in line with CIBSE Guide J [24].

$$DIF = GHR - DIR \qquad \text{Equation 2}$$

$$DNR = DIR / \sin(solar_{alt}) \qquad \text{Equation 3}$$

In order to avoid spikes of the direct normal radiation at low solar altitude angles, it was assumed as in the implementation of the Reindl solar separation model [25] in Daysim [26] that the direct normal radiation becomes equal to zero at solar altitude angles lower than 6°. Finally, the opaque sky cover, which is needed to calculate the horizontal infrared radiation intensity, since it is not included in the ERA5 database was estimated by assuming that is equal to 50% of the total sky cover (Jentsch, 2012).

A weather analysis of the RWD developed for three UK locations is presented in Appendix A.

3.2. Comparing the results obtained with the RWD files

To test the improved weather files, a case study building was simulated in EnergyPlus using the RWD for annual space heating energy demand and overheating assessment. The results were compared with those from using a TRY[8] for the annual space heating energy demand and a DSY for the overheating assessment. Three locations were considered: London, Manchester and Glasgow.

The case study building was an adjoining, two-bedroom, mid floor flat archetype[9] with a south orientation (Figure 1). It was chosen as a simple example and because flats can be prone to overheating in London. The flat's characteristics (including thermal and optical properties of the fabric elements as well as air flow data) can be found in Appendix B, Table B1.

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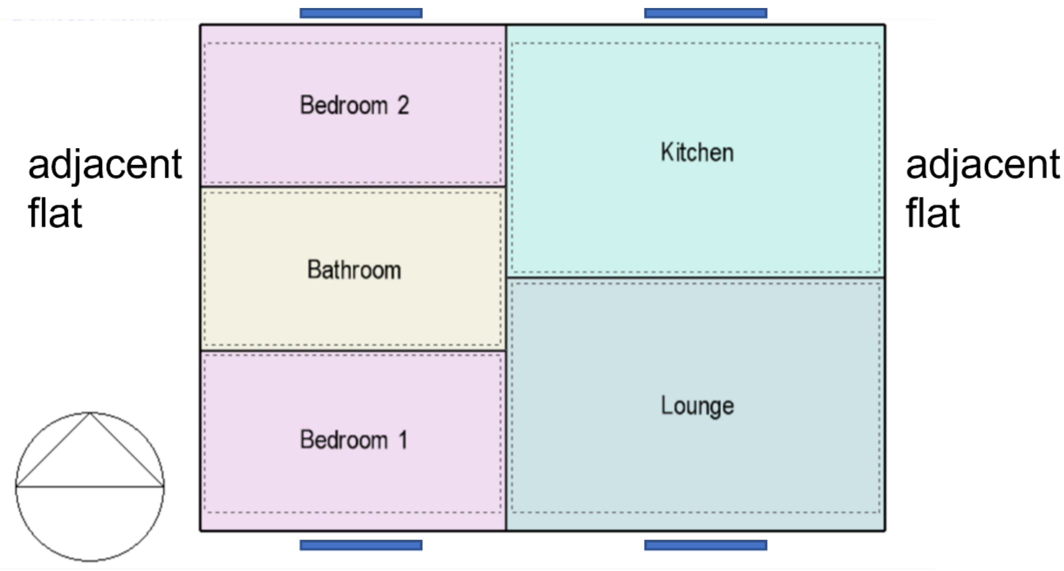
[8] TRY is a representative year of the years 2010-2019; see Appendix A for more details.
[9] The model of the case-study was created by the team at Leeds Becket University.

Figure 1: Plan of the case study flat.



3.2.1. Annual space heating energy demands

The case-study was simulated using the ideal loads air system in EnergyPlus; this component adds or removes heat at 100% efficiency in order to achieve and maintain the desired design conditions [28]. In this way the modelling of a detailed HVAC system which would have increased unnecessarily the complexity of the model is avoided. A constant heating setpoint equal to 20°C was chosen for all rooms. Gains from occupants, lights and equipment were obtained from the National Calculation Method[10] (NCM); these data can be found in Appendix B, Tables B2 and B3.

Table 1 presents the outcome of this analysis for the three selected locations. From Table 1 it can been seen that the annual space heating energy demand for London using the RWD varies from 2701 kWh to 4437 kWh and the mean annual space heating energy demand is 11.1% higher than that obtained from using the TRY. For Manchester, annual space heating energy demands using the RWD vary from 3790 kWh to 4966 kWh and the mean value is 12.5% higher than that obtained using the TRY. Finally, for Glasgow, annual space heating energy demands using the RWD vary from 4321 kWh to 5229 kWh and the mean value is 3.6% higher than that obtained from using the TRY.

[10] NCM is a procedure for demonstrating compliance with the building regulations. Available at https://www.uk-ncm.org.uk/download.jsp?id=13.

Table 1: Space heating energy demand (kWh) obtained using the RWD and the TRY for three different locations.

		Location		
Year	**Weather file**	**London**	**Manchester**	**Glasgow**
2010	RWD	4437	4966	5229
2011		3034	3798	4321
2012		3732	4632	4924
2013		4154	4586	4805
2014		2701	3790	4412
2015		2981	4077	4511
2016		3265	4096	4446
2017		3253	4066	4363
2018		3465	4430	4739
2019		3239	4154	4439
Mean value		3426	4260	4619
-	TRY	3046	3726	4452

This analysis demonstrates how much the space heating energy demand varies during the different years of a decade: up to 39.1% in the case of London in this simple example. A single year weather file cannot capture this variability and so the RWD file offers a better understanding of the performance of a building and can help to examine the effectiveness of different retrofit measures more thoroughly.

3.2.2. Overheating assessment

The overheating assessment employed the CIBSE TM59 adaptive criterion for assessing naturally ventilated homes (Equation 4):

$\Delta T = T_{op} - T_{max} \geq 1$ should not be more than 3% of the occupied hours for the period between May to September inclusive[11]. Equation 4

where,

T_{max} is the maximum acceptable temperature (°C) and it is calculated in accordance with CIBSE TM52

T_{op} is the operative temperature (°C) of the assessed room.

Overheating as in TM59, was assessed in all main spaces (i.e., living room, kitchen, and bedrooms). Gains from occupants, lights and equipment for each room[12], were ascribed to the model according to the TM59 guide. Two modelling scenarios were assessed; in the first (Modelling Scenario 1), windows were open[13] when the interior air temperature exceeded 22°C

[11] This criterion applies to lounges, kitchens and bedrooms.
[12] Different profiles are provided in TM59 for different room types.
[13] An opening factor of 0.5 was assumed.

and the examined room was occupied. In the second (Modelling Scenario 2), shades were operated on the same schedule as the windows (this means that windows and shades were opened or closed at the same time). The operation of the windows was modelled in EnergyPlus using the Zone Ventilation: Wind and Stack Open Area object. This object estimates the ventilation rates caused by opening a window as a function of wind speed and direction, and the opening's schedule of operation, area, and orientation [28].

The overheating assessment considered the living room, kitchen and both bedrooms and its outcome is shown in Tables 2-4. From Table 2, London: the living room did overheat according to the DSY (Scenario 1), but there was only overheating in four of the ten RWD years; there was no overheating in Bedroom 1 according to the DSY, but overheating did occur during one of the ten RWD years. There was no overheating in Manchester or Glasgow, regardless of which weather file was employed.

Table 2: TM59 criterion (% of occupied hours) for two different scenarios employing the RWD and DSY files for London. Values that exceed the 3% threshold are highlighted in red and bold.

		Scenario 1				Scenario 2			
Year	Weather file	Living room	Kitchen	Bedroom 1	Bedroom 2	Living room	Kitchen	Bedroom 1	Bedroom 2
2010	RWD	1.0	0	0.7	0.1	0.1	0	0.1	0
2011		1.9	0.3	1.2	0.2	0.3	0.2	0.1	0.1
2012		1.8	0	1.0	0.1	0.4	0	0.1	0
2013		**3.2**	0.6	1.7	0.5	1.1	0.5	0.5	0.3
2014		0.4	0	0.2	0.1	0.1	0	0	0
2015		1.2	0.6	0.7	0.4	0.8	0.6	0.4	0.3
2016		**3.4**	0.8	1.9	0.6	1.5	0.5	0.7	0.4
2017		2.0	0.8	1.0	0.5	0.9	0.4	0.5	0.3
2018		**7.0**	1.6	**3.7**	1.1	2.7	0.8	1.1	0.6
2019		**4.0**	2.6	2.4	1.5	**3.2**	2.2	1.6	1.3
	DSY	**3.2**	0.6	1.7	0.5	1.1	0.5	0.5	0.3

Table 3: TM59 criterion (% of occupied hours) for two different scenarios employing the RWD and DSY files for Manchester. Values that exceed the 3% threshold are highlighted in red and bold.

		Scenario 1				Scenario 2			
Year	**Weather file**	**Living room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Living room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**
2010	RWD	0.2	0	0.2	0	0	0	0	0
2011		0.6	0	0.4	0	0	0	0	0
2012		0	0	0.1	0	0	0	0	0
2013		0.5	0	0.3	0	0	0	0	0
2014		0	0	0	0	0	0	0	0
2015		0.7	0.3	0.4	0.2	0.3	0.2	0.2	0.1
2016		0.6	0.4	0.4	0.2	0.4	0.3	0.2	0.2
2017		0.9	0	0.5	0	0	0	0	0
2018		1.6	0	1	0.1	0.2	0	0.1	0
2019		1.5	0.3	0.9	0.2	0.5	0.2	0.2	0.1
	DSY	0.7	0	0.6	0	0	0	0	0

Table 4: TM59 criterion (% of occupied hours) for two different scenarios employing the RWD and DSY files for Glasgow. Values that exceed the 3% threshold are highlighted in red and bold.

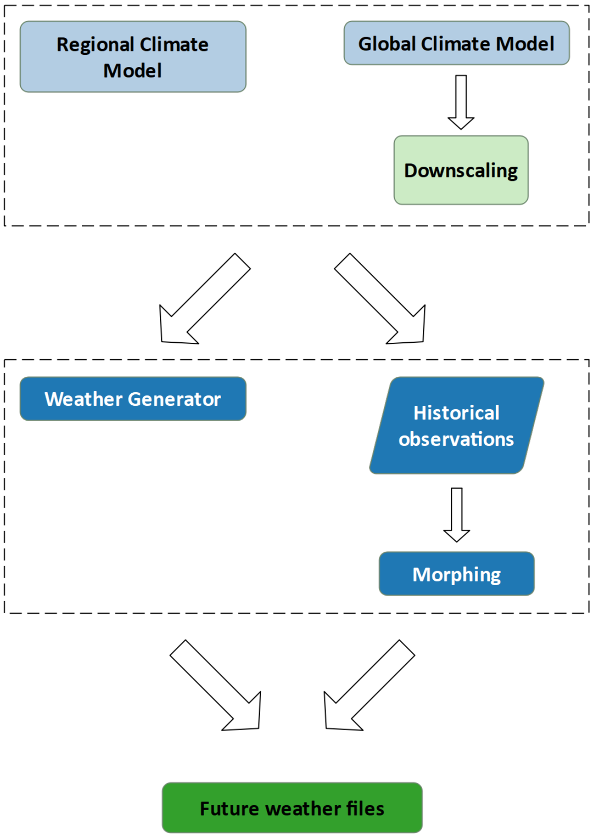
		Scenario 1				Scenario 2			
Year	**Weather file**	**Living room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**	**Living room**	**Kitchen**	**Bedroom 1**	**Bedroom 2**
2010	RWD	0	0	0.1	0	0	0	0	0
2011		0	0	0	0	0	0	0	0
2012		0	0	0.1	0	0	0	0	0
2013		0	0	0	0	0	0	0	0
2014		0.2	0	0.1	0	0	0	0	0
2015		0	0	0	0	0	0	0	0
2016		0.2	0	0.2	0	0	0	0	0
2017		0.3	0	0.2	0	0	0	0	0
2018		0.7	0.2	0.5	0.2	0.3	0	0.2	0.1
2019		0.5	0	0.5	0	0	0	0	0
	DSY	1	0	0.6	0	0	0	0	0

4. Future weather files

4.1. Future weather files used today

Future weather files are typically constructed either through a weather generator or by applying a morphing technique. As Figure 2 shows, a prerequisite for both methods is to obtain predictions of the future weather from a climate model. A climate model can simulate the global climate enclosing both the oceans and the atmosphere [29] and are grouped in two categories: the General Circulation Models (GCMs) and the Regional Climate Models (RCMs). They differ in the horizontal resolution of their outcomes; approximately equal to 100 and 10 km for the GCMs and the RCMs respectively [30]. However, climate predictions at a finer resolution (both spatial and temporal) can be obtained as well from a GCM by applying downscaling methods [29].

Figure 2: Illustration of the process of constructing future weather files.



A weather generator is a model that makes use of statistical correlations between weather parameters and produces timeseries outputs based on the provided climate projections [31]. The alternative morphing technique (see below for further details) involves the mathematical transformation of historical observations based on the climate projections. Either way, a weather file is generated that predicts the future weather [32]. CIBSE future weather files for building performance analysis were created using a morphing technique [13].

4.2. Constructing Future Weather Decade (FWD) files

For the construction of the Future Weather Decade (FWD) files used in this research the morphing technique was selected. The morphing technique is simple, flexible and transparent, and can be applied easily to various climate change scenarios [32]. Moreover, a consistency is achieved between a current and future weather file making the method attractive for assessing the performance of a building under both current and future weather conditions [5].

The morphing of the RWD files to create FWD files follows the method by Belcher [32]. Table 5 summarises the main similarities and differences between the morphing technique as implemented in this research and as implemented by CIBSE [13].

Table 5: Details of the morphing method.

Aspect of method	CIBSE future weather	FWD
Baseline weather	TRY, DSY	RWD
Climate variables morphed	Air temperature, relative humidity, atmospheric pressure, solar radiation, wind speed, rain, total cloud cover	
Source of climate projections	UKCP09	UKCP18
Nature of data	Probabilistic	Deterministic[1]
Spatial resolution	25 km	12 km
Temporal resolution	Monthly	
Emissions scenario	Low, medium and high	High
Predicted time slice	2020s, 2050s, 2080s	2060s

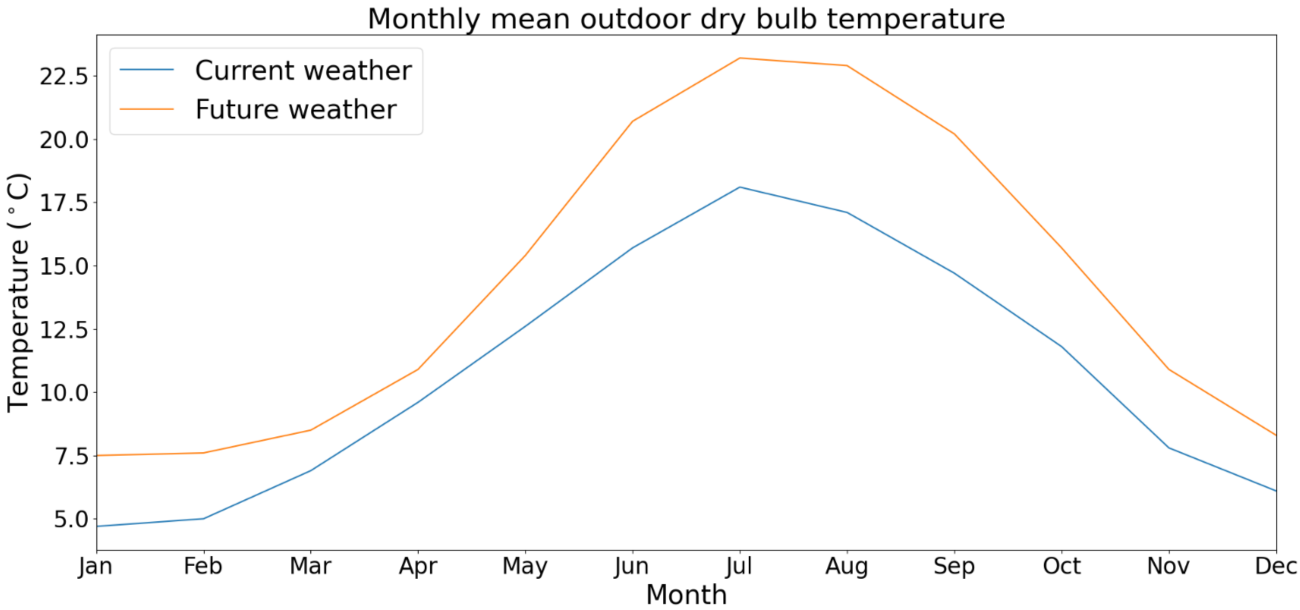
[1] However, aleatory uncertainty is taken into account by assessing twelve different climate scenarios.

The various morphing transformations (Table 6) are computed using UKCP18 projections for current (2010-2019) and future (2051-2070) weather. They are then applied to the real weather from the RWD (2010-2019). For each weather parameter, and for each month, a monthly average value is computed, and the transformations calculated relative to these averages (see Appendix C). Figure 3 displays difference in air temperature now and in the future based on UKCP18 projections for London. A comparison between the RWD and FWD for the three examined locations is presented in Appendix D.

Table 6: Mathematical transformations applied to the weather variables.

Weather variable	**Morphing transformation** (Belcher et al., 2005)
Air temperature	Shift and stretch
Relative humidity	Stretch
Global horizontal radiation	Stretch
Wind speed	Stretch
Rain	Stretch
Total cloud cover	Shift
Atmospheric pressure	Shift

Figure 3: Comparing monthly mean outdoor air dry bulb temperature for London.



The UKCP18 projections include global horizontal radiation, but there are no data for direct normal and diffuse radiation. Therefore, morphed values of the components of the global radiation were derived by employing the Skartveit and Olseth separation model [33]. It has been shown that this model performs very well especially when it is compared to the CRM [34] [7].

To illustrate this, values of direct normal radiation (DNR) and diffuse horizontal radiation (DIF) were derived from the Skartveit and Olseth radiation model (SORM) and the CRM[14] and they were compared against the respective values obtained from the ERA5 database (for the years 2010-2019). This comparison was performed for London, Manchester and Glasgow as shown in Figures 4-6. These figures show clearly that values of DNR and DIF obtained from SORM are much better correlated to the ERA5 data (they have a larger coefficient of determination (R^2)) than the respective values obtained from CRM (which are highly scattered). Moreover, Figures 4-6 show clearly that location does not affect the correlation between the two inspected models and the ERA5 values; the derived R^2 values are very similar for all the three examined locations highlighting the fact that the predicted capability of the model does not depend on location.

[14] For both models the global horizontal radiation obtained from ERA5 database was used to derive the two components of it.

Figure 4: Comparison between direct normal (DNR) and horizontal diffuse (DIF) radiation, obtained from the Skartveit and Olseth separation model and the CRM against the data obtained from the ERA5 database for London.

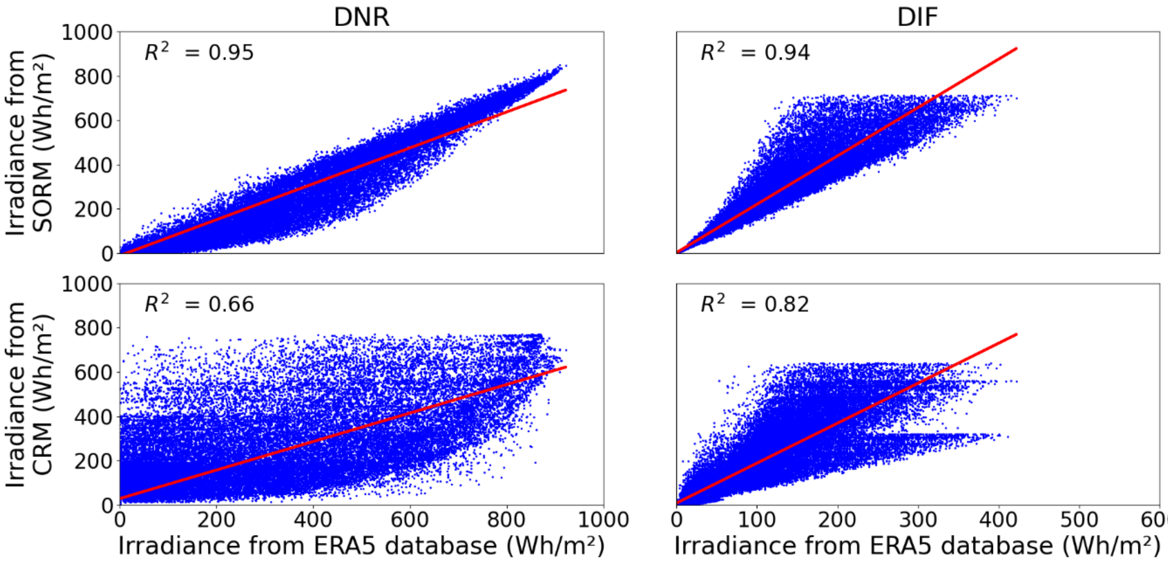


Figure 5: Comparison between direct normal (DNR) and horizontal diffuse (DIF) radiation, obtained from the Skartveit and Olseth separation model and the CRM against the data obtained from the ERA5 database for Manchester.

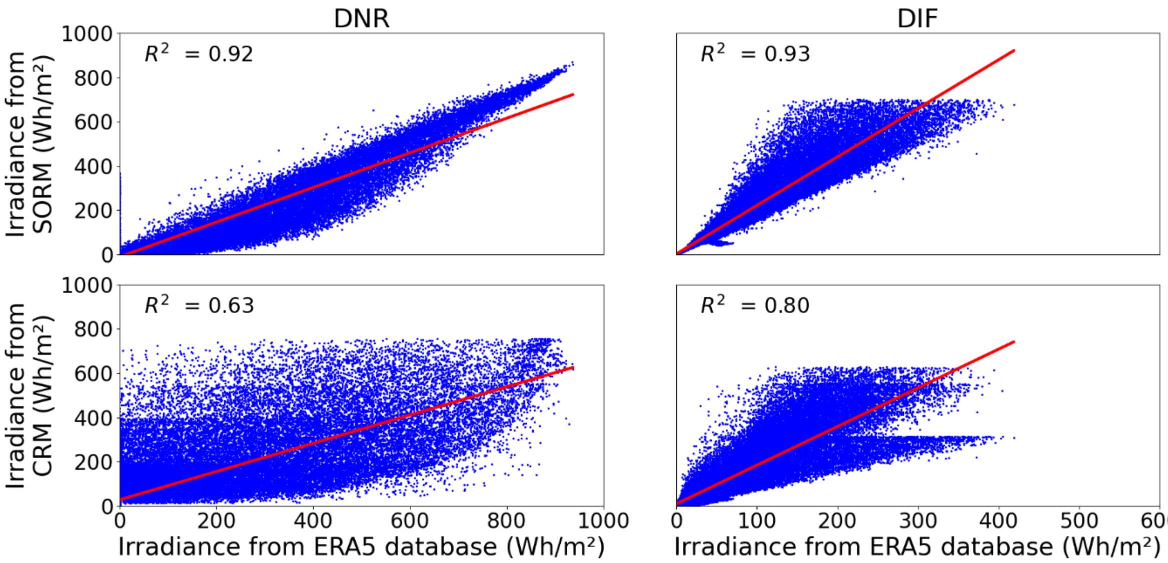
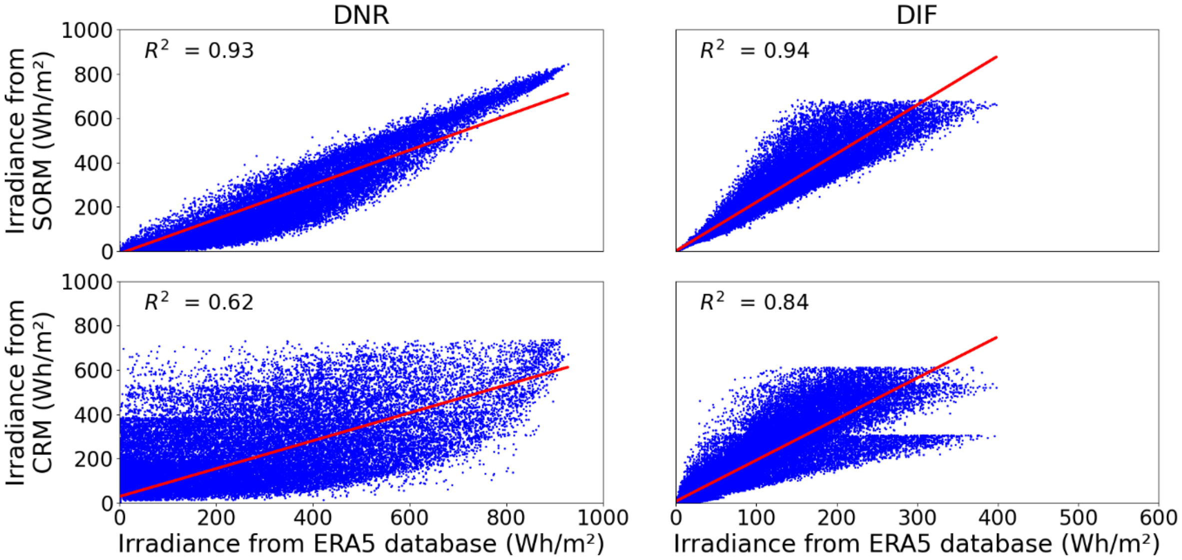


Figure 6: Comparison between direct normal (DNR) and horizontal diffuse (DIF) radiation, obtained from the Skartveit and Olseth separation model and the CRM against the data obtained from the ERA5 database for Glasgow.



The UKCP18 projections include twelve different scenarios to incorporate the uncertainty in regional as well as in large scale climate conditions [35] as detailed by Yamazaki et al. [36]. These twelve scenarios were originated from a larger pool of scenarios (25 in total). Their choice was made on the basis to create as much diversity as possible in terms of CO_2, aerosol forcing[15] and sea surface temperature [37].

Twelve FWD files, each containing ten years of weather data, can be created: one for each of the twelve scenarios. Monthly average daily maximum temperature, monthly solar radiation and monthly precipitation values are displayed for all twelve scenarios and for the three examined locations in Appendix E.

4.3. Comparing the results obtained with the FWD files

The case study building (section 3.2) was simulated in EnergyPlus using the FWD (and all twelve future weather scenarios (Sc1 to Sc12)) for annual space heating energy demand and overheating assessment, using the same modelling assumptions, for London, Manchester and Glasgow.

4.3.1. Annual space heating energy demands

The annual space heating energy demands for the twelve scenarios, across the three locations, are shown in Figures 7-9. There is variability between the results from different scenarios. The results are presented as box plots that show the median, lower and upper

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[15] The impact of aerosols due to anthropogenic or natural sources on climate [44].

quartiles, and whiskers that display the remaining data. The whiskers are equal to the interquartile range multiplied by 1.5; any data outside this range are shown as outliers (dots).

Figure 7 shows that for London, future annual space heating energy demands range from 1600 kWh (Scenario 6) to 3960 kWh (Scenario 4). Mean annual space heating energy demands range from 2200 kWh (Scenario 6) to 2967kWh (Scenario 4) (a 25.9% increase) with the average annual space heating energy demand across all scenarios being 2492kWh.

Figure 8 shows that for Manchester, future annual space heating energy demands range from 2630kWh (Scenario 6) to 4464kWh (Scenario 4). Mean annual space heating energy demands range from 3016kWh (Scenario 6) to 3791 kWh (Scenario 4) (a 20.5 % increase) with the average annual space heating energy demand across all scenarios being 3277 kWh.

Figure 7: Space heating energy demand for twelve different future climate scenarios for the case study flat located in London.

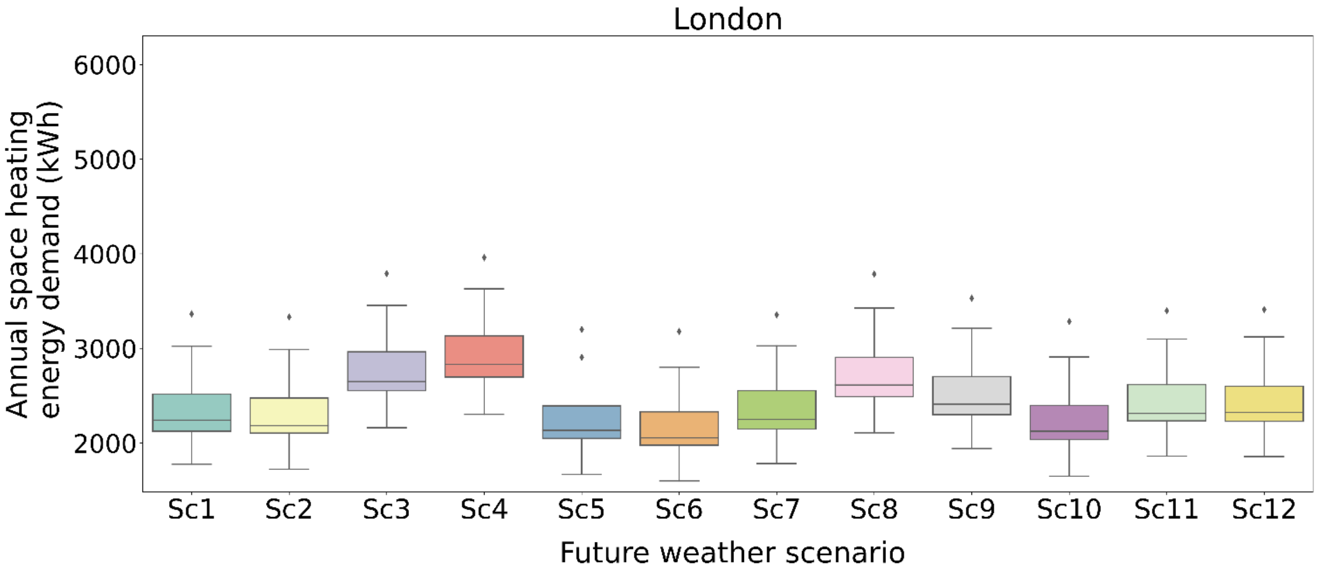


Figure 8: Space heating energy demand for twelve different future climate scenarios for the case study flat located in Manchester.

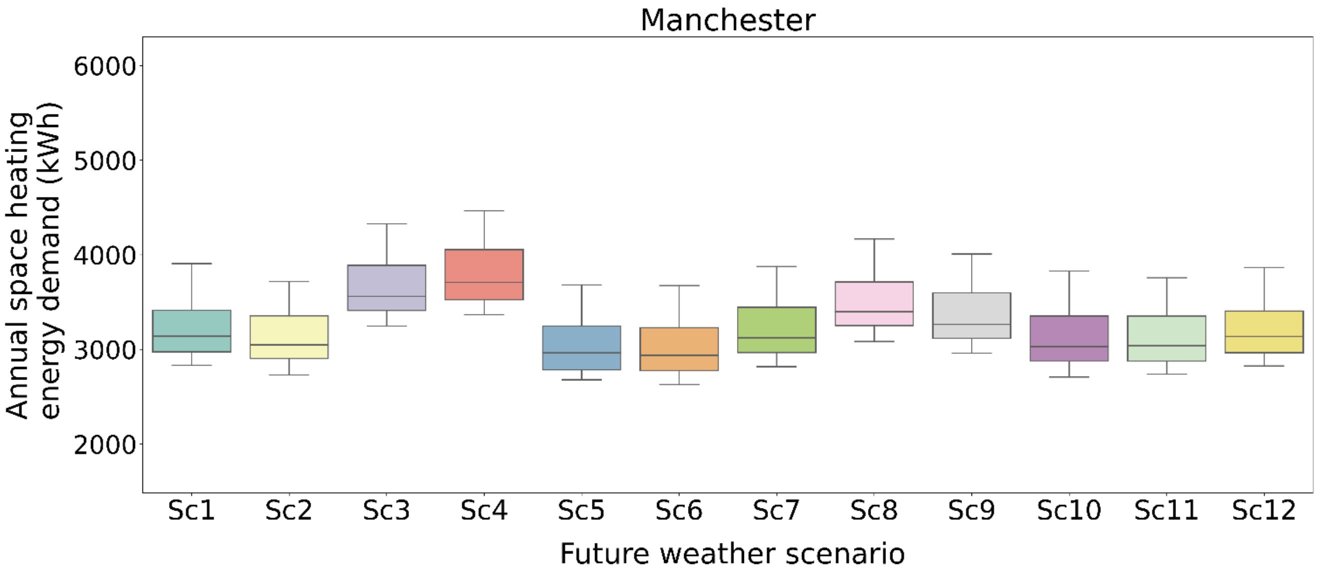
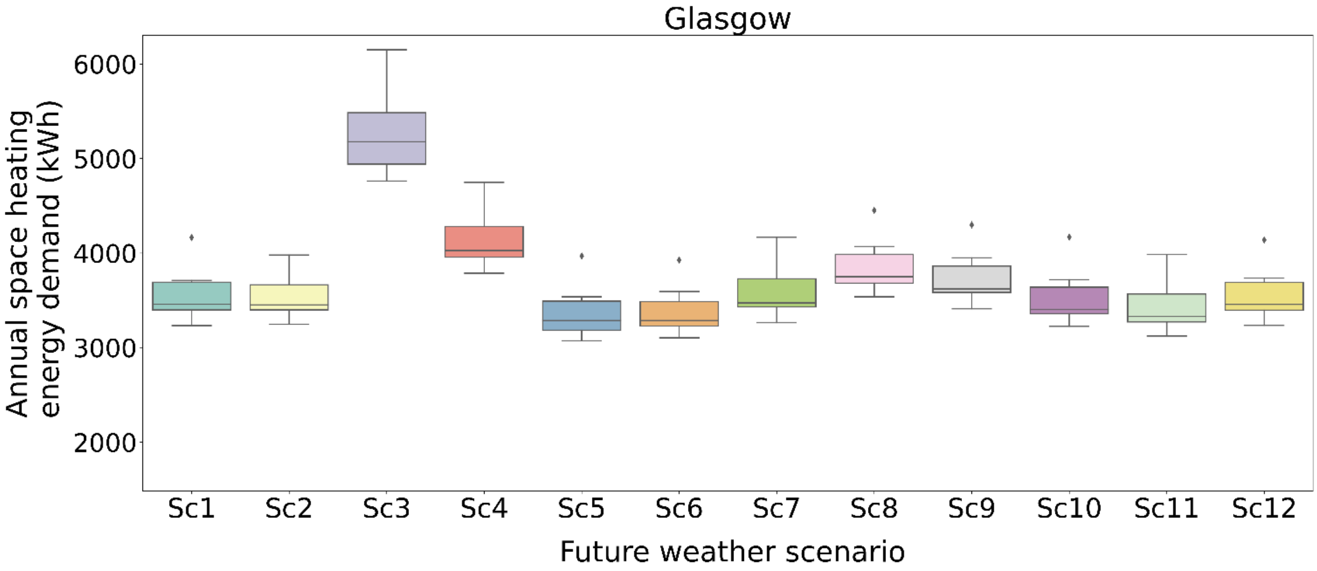


Figure 9 shows that for Glasgow, future annual space heating energy demands range from 3073 kWh (Scenario 5) to 6150 kWh (Scenario 3). Mean annual space heating energy demands range from 3361 kWh (Scenario 5) to 5258 kWh (Scenario 3) (a 36.1% increase) with the average annual space heating energy demand across all scenarios being 3734 kWh.

Figure 9: Space heating energy demand for twelve different future climate scenarios for the case study flat located in Glasgow.



4.3.2. Overheating assessment

The results of the overheating assessment are shown in Tables 10-15. There is clearly some uncertainty in future weather that impacts the results. For example, for London and considering Modelling Scenario 1[16], the minimum value of the threshold value in the living room ranges from 0.3 to 4.5% while the maximum respective value ranges from 9.1 to 17.1% (Table 10). In the context of the TM59 criteria, the magnitude of the influence of the choice of the future weather scenario on the outcome of the analysis depends on location, the room under examination and whether shades were employed. For example, considering London and Modelling Scenario 1, the threshold value in the living room is exceeded in all years and in all future weather scenarios (Table 10). However, in the same city but under Modelling Scenario 2, and looking into the bedroom there are two future weather scenarios that the threshold value is exceed only once, while there are two other future weather scenarios that the threshold value is exceeded in seven years (Table 11). On the contrary, considering Glasgow, the choice of the future weather scenario exerts no impact on the outcome of the analysis. The threshold value is never exceeded unless once in the living room under Modelling Scenario 1 (Table 14). The following section considers how to present the various results in a simpler form.

[16] In Modelling Scenario 1 windows can open if certain conditions are met. In Modelling Scenario 2 shades can also be deployed; see Section 3.2.2.

Table 10: TM59 criterion (% of occupied hours) for the living room of the case study flat under two different scenarios employing the FWD file for London. Values that exceed the 3% threshold are highlighted in red and bold.

		Future weather scenario											
Modelling scenario	**Baseline period**	Sc1	Sc 2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Sc11	Sc12
Scenario 1	2010	**10.4**	**6.9**	**6.0**	**8.3**	**8.3**	**7.5**	**5.2**	**6.9**	**10.1**	**8.5**	**7.8**	**11.2**
	2011	**7.8**	**5.4**	**5.6**	**5.5**	**6.3**	**6.2**	**5.2**	**5.5**	**6.3**	**6.6**	**5.5**	**7.4**
	2012	**11.0**	**9.7**	**9.4**	**8.4**	**10.0**	**9.9**	**8.2**	**8.7**	**8.1**	**10.4**	**8.8**	**11.2**
	2013	**17.1**	**12.5**	**11.7**	**9.9**	**11.3**	**12.6**	**8.4**	**11.4**	**13.6**	**14.3**	**11.5**	**14.8**
	2014	**12.9**	**8.2**	**6.2**	**8.0**	**7.8**	**8.3**	**3.9**	**7.8**	**11.0**	**9.0**	**8.5**	**12.2**
	2015	**7.8**	**5.2**	**4.5**	**4.7**	**5.4**	**5.4**	**3.2**	**4.2**	**6.9**	**6.3**	**4.6**	**7.9**
	2016	**14.9**	**11.3**	**10.7**	**9.3**	**11.6**	**11.7**	**8.6**	**9.6**	**11.3**	**12.8**	**9.9**	**14.0**
	2017	**11.9**	**9.5**	**8.7**	**8.5**	**9.4**	**9.3**	**6.6**	**8.2**	**9.8**	**10.1**	**8.6**	**11.9**
	2018	**24.9**	**19.8**	**18.9**	**19.7**	**21.2**	**20.9**	**16.2**	**19.0**	**21.6**	**21.4**	**19.7**	**24.7**
	2019	**15.5**	**11.2**	**9.9**	**8.9**	**9.5**	**10.9**	**7.6**	**9.7**	**12.2**	**12.5**	**9.9**	**13.9**
	Min.	**7.8**	**5.2**	**4.5**	**4.7**	**5.4**	**5.4**	**3.2**	**4.2**	**6.3**	**6.3**	**4.6**	**7.4**
	Max.	**24.9**	**19.8**	**18.9**	**19.7**	**21.2**	**20.9**	**16.2**	**19.0**	**21.6**	**21.4**	**19.7**	**24.7**
Scenario 2	2010	**5.7**	3.0	**3.1**	**4.8**	**4.4**	**4.1**	2.4	**3.9**	**5.4**	**4.3**	**4.3**	**7.1**
	2011	**4.8**	**3.3**	**3.7**	**3.1**	**3.9**	**3.9**	**3.6**	**3.5**	**3.9**	**4.2**	**3.4**	**4.6**
	2012	**6.7**	**5.0**	**4.7**	**4.2**	**5.4**	**5.1**	**3.3**	**4.1**	**4.9**	**5.9**	**4.3**	**6.6**
	2013	**11.2**	**7.5**	**6.1**	**5.9**	**5.5**	**7.1**	**3.9**	**6.9**	**9.0**	**7.4**	**7.3**	**9.2**
	2014	**7.5**	**3.6**	2.2	2.7	1.9	**3.1**	0.3	2.9	**5.2**	2.9	**3.3**	**5.3**
	2015	**4.5**	2.8	2.7	1.6	2.4	2.5	1.8	1.7	**3.1**	**3.6**	1.7	**3.9**
	2016	**9.5**	**7.1**	**6.9**	**5.1**	**6.4**	**7.1**	**5.3**	**6.0**	**7.0**	**8.2**	**6.1**	**8.4**
	2017	**7.1**	**5.1**	**4.5**	**5.1**	**5.5**	**5.0**	**3.4**	**4.7**	**6.5**	**5.5**	**4.9**	**7.2**
	2018	**17.1**	**13.7**	**12.1**	**13.8**	**13.1**	**13.5**	**9.1**	**12.9**	**15.1**	**14.6**	**13.6**	**17.1**
	2019	**9.2**	**6.4**	**6.1**	**5.3**	**6.0**	**6.4**	**5.2**	**5.9**	**7.5**	**7.2**	**5.9**	**7.8**
	Min.	**4.5**	2.8	2.2	1.6	1.9	2.5	0.3	1.7	**3.1**	2.9	1.7	**3.9**
	Max.	**17.1**	**13.7**	**12.1**	**13.8**	**13.1**	**13.5**	**9.1**	**12.9**	**15.1**	**14.6**	**13.6**	**17.1**

Table 11: TM59 criterion (% of occupied hours) for bedroom 1 of the case study flat under two different scenarios employing the FWD file for London. Values that exceed the 3% threshold are highlighted in red and bold.

		Future weather scenario											
Modelling scenario	**Baseline period**	Sc1	Sc 2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Sc11	Sc12
Scenario 1	2010	**5.1**	**3.6**	**3.2**	**4.2**	**4.2**	**3.9**	2.7	**3.5**	**5.0**	**4.2**	**3.9**	**5.7**
	2011	**4.3**	3.0	**3.1**	3.0	**3.5**	**3.4**	2.9	**3.1**	**3.5**	**3.6**	3.0	**4.2**
	2012	**6.1**	**5.3**	**5.0**	**4.4**	**5.3**	**5.3**	**4.3**	**4.6**	**4.4**	**5.5**	**4.6**	**5.9**
	2013	**9.1**	**6.5**	**6.1**	**5.2**	**6.0**	**6.6**	**4.4**	**5.9**	**7.1**	**7.4**	**6.0**	**7.8**
	2014	**6.7**	**4.2**	**3.2**	**4.0**	**4.0**	**4.2**	2.1	**4.0**	**5.6**	**4.5**	**4.4**	**6.1**
	2015	**4.3**	2.9	2.5	2.6	2.9	3.0	1.9	2.5	**3.6**	**3.5**	2.6	4.4
	2016	**8.4**	**6.2**	**5.9**	**5.0**	**6.3**	**6.5**	**4.7**	**5.3**	**6.2**	**6.9**	**5.4**	**7.6**
	2017	**6.1**	**5.0**	**4.6**	**4.4**	**5.0**	**5.0**	**3.6**	**4.4**	**5.1**	**5.3**	**4.4**	**6.3**
	2018	**13.6**	**10.6**	**10.1**	**10.3**	**11.3**	**11.2**	**8.5**	**10.2**	**11.5**	**11.6**	**10.4**	**13.3**
	2019	**8.8**	**6.2**	**5.5**	**4.9**	**5.4**	**6.1**	**4.3**	**5.3**	**6.9**	**7.0**	**5.5**	**7.8**
	Min.	**4.3**	2.9	2.5	2.6	2.9	3.0	1.9	2.5	**3.5**	**3.5**	2.6	**4.2**
	Max.	**13.6**	**10.6**	**10.1**	**10.3**	**11.3**	**11.2**	**8.5**	**10.2**	**11.5**	**11.6**	**10.4**	**13.3**
Scenario 2	2010	2.7	1.3	1.3	2.3	2.1	1.9	1.1	1.8	2.5	2.0	2.1	3.1
	2011	2.4	1.7	2.0	1.6	2.0	2.0	1.9	1.8	2.0	2.2	1.8	2.4
	2012	**3.2**	2.4	2.2	2.0	2.4	2.4	1.6	2.0	2.4	2.8	2.0	**3.2**
	2013	**5.4**	**3.4**	2.8	2.7	2.5	**3.2**	1.9	**3.1**	**4.3**	**3.3**	**3.3**	**4.3**
	2014	**3.4**	1.6	0.9	1.1	0.7	1.2	0.2	1.3	2.2	1.2	1.4	2.1
	2015	2.2	1.5	1.5	0.9	1.2	1.3	0.9	0.9	1.5	1.7	0.9	2.0
	2016	**5.0**	**3.4**	**3.4**	2.4	2.9	**3.4**	2.5	2.9	**3.4**	**4.1**	2.9	**4.2**
	2017	**3.3**	2.2	2.1	2.5	2.6	2.3	1.5	2.1	**3.1**	2.6	2.3	**3.5**
	2018	**8.7**	**6.8**	**5.8**	**6.5**	**6.2**	**6.6**	**4.2**	**6.3**	**7.6**	**7.0**	**6.6**	**8.4**
	2019	**4.8**	**3.3**	**3.2**	2.9	**3.1**	**3.3**	2.8	**3.1**	**3.8**	**3.8**	**3.2**	**4.2**
	Min.	2.2	1.3	0.9	0.9	0.7	1.2	0.2	0.9	1.5	1.2	0.9	2.0
	Max.	**8.7**	**6.8**	**5.8**	**6.5**	**6.2**	**6.6**	**4.2**	**6.3**	**7.6**	**7.0**	**6.6**	**8.4**

Table 12: TM59 criterion (% of occupied hours) for the living room of the case study flat under two different scenarios employing the FWD file for Manchester. Values that exceed the 3% threshold are highlighted in red and bold.

Modelling scenario	Baseline period	Future weather scenario											
		Sc1	Sc 2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Sc11	Sc12
Scenario 1	2010	2.1	1.4	1.0	2.7	2.9	2.8	1.5	1.5	**3.4**	1.9	1.3	4.1
	2011	**3.2**	1.5	2.3	2.5	2.2	2.3	2.1	1.9	2.7	2.5	2.2	3.0
	2012	2.6	2.3	0.9	3.0	2.7	1.8	0.9	1.5	1.5	2.1	1.9	2.6
	2013	**6.7**	**3.8**	**5.0**	**4.5**	2.0	**3.4**	2.2	3.2	**5.9**	**4.0**	**4.9**	**4.9**
	2014	**3.4**	1.8	2.3	2.6	1.0	1.5	1.0	1.8	**3.1**	1.5	2.6	2.2
	2015	2.1	1.3	1.9	1.4	1.1	1.3	1.2	1.2	1.8	2.1	1.5	2.4
	2016	**5.4**	**3.2**	**3.7**	**3.7**	3.0	**3.8**	2.5	2.8	**3.8**	**4.7**	3.0	**5.5**
	2017	2.8	2.3	2.3	**3.5**	3.0	3.0	2.5	2.7	**3.6**	3.0	2.9	**3.9**
	2018	**10.3**	**7.8**	**8.3**	**10.2**	**7.0**	**7.5**	**5.2**	**7.2**	**10.1**	**7.7**	**8.7**	**10.1**
	2019	**5.7**	**4.2**	**5.0**	**4.1**	**3.2**	**4.2**	**3.4**	**3.7**	**4.8**	**5.5**	**4.4**	**5.8**
	Min.	2.1	1.3	0.9	1.4	1.0	1.3	0.9	1.2	1.5	1.5	1.3	2.2
	Max.	**10.3**	**7.8**	**8.3**	**10.2**	**7.0**	**7.5**	**5.2**	**7.2**	**10.1**	**7.7**	**8.7**	**10.1**
Scenario 2	2010	0.1	0.7	0.0	1.0	1.0	0.7	0.1	0.6	0.6	0.5	0.2	1.3
	2011	1.6	0.5	1.1	1.3	1.2	1.4	1.1	0.9	1.5	1.2	1.0	1.9
	2012	0.1	0.5	0.0	0.9	0.9	0.2	0.0	0.2	0.0	0.4	0.1	0.4
	2013	3.1	1.2	1.8	1.7	0.5	1.0	0.6	1.0	2.9	1.6	1.9	1.9
	2014	1.8	0.5	0.9	1.1	0.0	0.0	0.0	0.5	1.9	0.0	1.1	0.8
	2015	1.1	0.8	1.0	1.0	0.9	1.0	0.8	0.9	1.2	1.1	1.0	1.2
	2016	2.5	1.1	1.4	1.6	1.0	1.2	0.8	0.7	2.1	1.0	1.3	2.2
	2017	1.3	1.2	0.6	2.0	1.9	2.0	1.2	1.4	1.9	1.4	1.3	2.4
	2018	**5.5**	2.3	**4.0**	**4.9**	2.7	**3.1**	2.1	2.7	**6.1**	**3.2**	**4.0**	**5.2**
	2019	**3.8**	2.4	**3.1**	2.5	1.7	2.3	2.1	1.7	**3.4**	**3.1**	2.8	**3.3**
	Min.	0.1	0.5	0.0	0.9	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.4
	Max.	**5.5**	2.4	**4.0**	**4.9**	2.7	**3.1**	2.1	2.7	**6.1**	**3.2**	**4.0**	**5.2**

Table 13: TM59 criterion (% of occupied hours) for bedroom 1 of the case study flat under two different scenarios employing the FWD file for Manchester. Values that exceed the 3% threshold are highlighted in red and bold.

Modelling scenario	Baseline period	Future weather scenario											
		Sc1	Sc 2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Sc11	Sc12
Scenario 1	2010	1.2	0.8	0.5	1.5	1.6	1.6	0.8	0.8	1.9	1.0	0.7	2.3
	2011	1.8	1.0	1.3	1.4	1.3	1.3	1.2	1.1	1.5	1.4	1.2	1.7
	2012	1.5	1.3	0.6	1.7	1.5	1.1	0.6	1.0	0.9	1.3	1.1	1.4
	2013	**3.4**	2.1	2.7	2.5	1.3	1.9	1.3	1.9	3.1	2.3	2.6	2.8
	2014	1.8	0.9	1.2	1.4	0.6	0.8	0.5	0.9	1.6	0.8	1.3	1.2
	2015	1.4	0.8	1.1	0.8	0.6	0.8	0.6	0.7	1.1	1.2	0.8	1.5
	2016	3.0	1.9	2.2	2.2	1.8	2.2	1.6	1.7	2.3	2.6	1.9	**3.1**
	2017	1.6	1.3	1.3	1.9	1.7	1.7	1.3	1.5	2.0	1.7	1.6	2.2
	2018	**5.5**	**4.4**	**4.3**	**5.5**	**3.9**	**4.1**	2.8	**3.9**	**5.3**	**4.1**	**4.6**	**5.5**
	2019	**3.5**	2.5	2.9	2.5	1.9	2.5	2.0	2.2	2.8	3.2	2.6	3.4
	Min.	1.2	0.8	0.5	0.8	0.6	0.8	0.5	0.7	0.9	0.8	0.7	1.2
	Max.	**5.5**	**4.4**	**4.3**	**5.5**	**3.9**	**4.1**	2.8	**3.9**	**5.3**	**4.1**	**4.6**	**5.5**
Scenario 2	2010	0.0	0.3	0.0	0.4	0.4	0.2	0.0	0.2	0.2	0.2	0.1	0.5
	2011	0.8	0.3	0.5	0.7	0.6	0.7	0.6	0.5	0.8	0.6	0.5	1.0
	2012	0.0	0.2	0.0	0.4	0.4	0.1	0.0	0.1	0.0	0.2	0.1	0.2
	2013	1.4	0.5	0.8	0.8	0.3	0.5	0.3	0.4	1.3	0.7	0.9	0.8
	2014	0.7	0.1	0.4	0.4	0.0	0.0	0.0	0.0	0.8	0.0	0.5	0.3
	2015	0.6	0.4	0.5	0.5	0.4	0.5	0.4	0.4	0.7	0.5	0.5	0.6
	2016	1.3	0.6	0.7	0.8	0.5	0.6	0.4	0.4	1.1	0.6	0.6	1.1
	2017	0.6	0.6	0.3	1.0	0.9	0.9	0.6	0.7	0.9	0.7	0.6	1.2
	2018	2.4	1.0	1.7	2.3	1.3	1.5	1.0	1.2	2.8	1.5	1.8	2.3
	2019	2.0	1.2	1.4	1.1	0.9	1.1	1.0	0.9	1.8	1.5	1.2	1.6
	Min.	0.0	0.1	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
	Max.	2.4	1.2	1.7	2.3	1.3	1.5	1.0	1.2	2.8	1.5	1.8	2.3

Table 14: TM59 criterion (% of occupied hours) for the living room of the case study flat under two different scenarios employing the FWD file for Glasgow. Values that exceed the 3% threshold are highlighted in red and bold.

Modelling scenario	Baseline period	Future weather scenario											
		Sc1	Sc 2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Sc11	Sc12
Scenario 1	2010	0.4	0.2	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.1	0.0	0.1
	2011	0.4	0.0	0.0	0.1	0.1	0.2	0.0	0.0	0.5	0.0	0.0	0.5
	2012	1.2	2.2	0.2	2.5	2.6	1.7	0.6	1.4	0.5	2.3	1.1	1.6
	2013	2.1	1.1	2.1	2.0	0.7	1.0	0.9	1.3	2.6	1.0	2.1	1.6
	2014	1.7	0.9	1.5	1.4	0.6	1.2	0.7	1.0	2.1	0.8	1.5	1.6
	2015	0.9	0.5	0.7	0.6	0.2	0.5	0.4	0.4	0.9	0.6	0.8	0.8
	2016	1.2	1.0	1.1	1.0	0.7	1.3	0.9	0.5	1.4	1.3	1.2	1.6
	2017	1.0	1.1	0.6	1.3	0.9	1.0	0.4	1.0	0.9	1.0	1.0	1.1
	2018	2.3	1.4	2.2	3.0	2.3	2.7	1.9	1.9	**3.7**	2.1	2.7	**3.2**
	2019	2.4	1.4	1.9	2.4	2.2	1.9	1.8	1.5	2.3	2.3	2.1	2.3
	Min.	0.4	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	Max.	2.4	2.2	2.2	3.0	2.6	2.7	1.9	1.9	3.7	2.3	2.7	**3.2**
Scenario 2	2010	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2011	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2012	0.0	0.4	0.0	0.8	0.9	0.0	0.0	0.0	0.0	0.2	0.0	0.0
	2013	0.7	0.0	0.1	0.8	0.0	0.0	0.0	0.0	1.2	0.0	0.9	0.4
	2014	0.7	0.2	0.4	0.7	0.0	0.2	0.0	0.3	1.0	0.1	0.7	0.6
	2015	0.3	0.0	0.2	0.3	0.0	0.0	0.0	0.0	0.4	0.1	0.3	0.2
	2016	0.4	0.3	0.4	0.4	0.2	0.3	0.2	0.3	0.5	0.5	0.4	0.5
	2017	0.1	0.5	0.0	0.7	0.7	0.3	0.0	0.3	0.3	0.4	0.2	0.3
	2018	0.6	0.4	0.4	0.9	0.9	1.2	0.9	0.7	1.4	0.8	0.8	1.3
	2019	0.8	0.5	0.5	0.6	0.2	1.0	0.4	0.3	1.2	0.6	0.7	1.2
	Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max.	0.8	0.5	0.5	0.9	0.9	1.2	0.9	0.7	1.4	0.8	0.9	1.3

Table 15: TM59 criterion (% of occupied hours) for bedroom 1 of the case study flat under two different scenarios employing the FWD file for Glasgow. Values that exceed the 3% threshold are highlighted in red and bold.

		Future weather scenario											
Modelling scenario	**Baseline period**	Sc1	Sc 2	Sc3	Sc4	Sc5	Sc6	Sc7	Sc8	Sc9	Sc10	Sc11	Sc12
Scenario 1	2010	0.3	0.2	0.0	0.3	0.3	0.1	0.0	0.0	0.1	0.2	0.0	0.3
	2011	0.4	0.1	0.1	0.2	0.3	0.3	0.2	0.2	0.4	0.2	0.1	0.4
	2012	0.7	1.4	0.1	1.5	1.5	1.0	0.5	0.8	0.5	1.3	0.7	0.9
	2013	1.1	0.7	1.2	1.1	0.4	0.6	0.5	0.8	1.4	0.6	1.1	0.9
	2014	1.1	0.6	0.9	0.8	0.4	0.7	0.5	0.6	1.2	0.6	0.9	1.0
	2015	0.8	0.5	0.6	0.5	0.3	0.5	0.4	0.4	0.7	0.5	0.5	0.6
	2016	0.8	0.7	0.7	0.8	0.6	0.9	0.7	0.4	1.0	0.8	0.7	1.0
	2017	0.6	0.7	0.4	0.9	0.7	0.6	0.4	0.6	0.6	0.6	0.6	0.6
	2018	1.3	0.9	1.2	1.7	1.4	1.6	1.2	1.1	1.9	1.2	1.4	1.8
	2019	1.5	1.1	1.2	1.5	1.3	1.2	1.1	0.9	1.4	1.4	1.2	1.5
	Min.	0.3	0.1	0.0	0.2	0.3	0.1	0.0	0.0	0.1	0.2	0.0	0.3
	Max.	1.5	1.4	1.2	1.7	1.5	1.6	1.2	1.1	1.9	1.4	1.4	1.8
Scenario 2	2010	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2011	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2012	0.0	0.1	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.1	0.0	0.0
	2013	0.3	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.6	0.0	0.3	0.1
	2014	0.3	0.1	0.2	0.3	0.0	0.1	0.0	0.1	0.5	0.0	0.3	0.3
	2015	0.2	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.1	0.2	0.1
	2016	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.3	0.3	0.2	0.3
	2017	0.1	0.3	0.0	0.4	0.4	0.2	0.0	0.2	0.1	0.2	0.1	0.2
	2018	0.3	0.2	0.2	0.5	0.4	0.6	0.4	0.4	0.7	0.4	0.4	0.6
	2019	0.4	0.3	0.3	0.3	0.1	0.5	0.2	0.2	0.6	0.3	0.4	0.6
	Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Max.	0.4	0.3	0.3	0.5	0.4	0.6	0.4	0.4	0.7	0.4	0.4	0.6

5. Presenting the results

5.1. Annual space heating energy demands

Figures 10-12 show the annual space heating energy demand results for the case study building, from using the RWD, along with the results from the FWD scenarios. For simplicity, only these three out of the twelve FWDs (see Section 4.2) were included. They were chosen as the ones with the total space heating energy over the ten years being nearest to the 5%, 50% and 95% percentiles of the total space heating energy in all future weather scenarios. This contrasts with the current method only showing a single outcome using the TRY. This way of presenting the future weather results is similar to CIBSE TM54:2013 where the operational space heating energy demand of a building is computed for three different scenarios which reflect different levels of effective management, operational hours and internal gains [38].

Figure 10: Annual space heating energy demand for the case-study building in London.

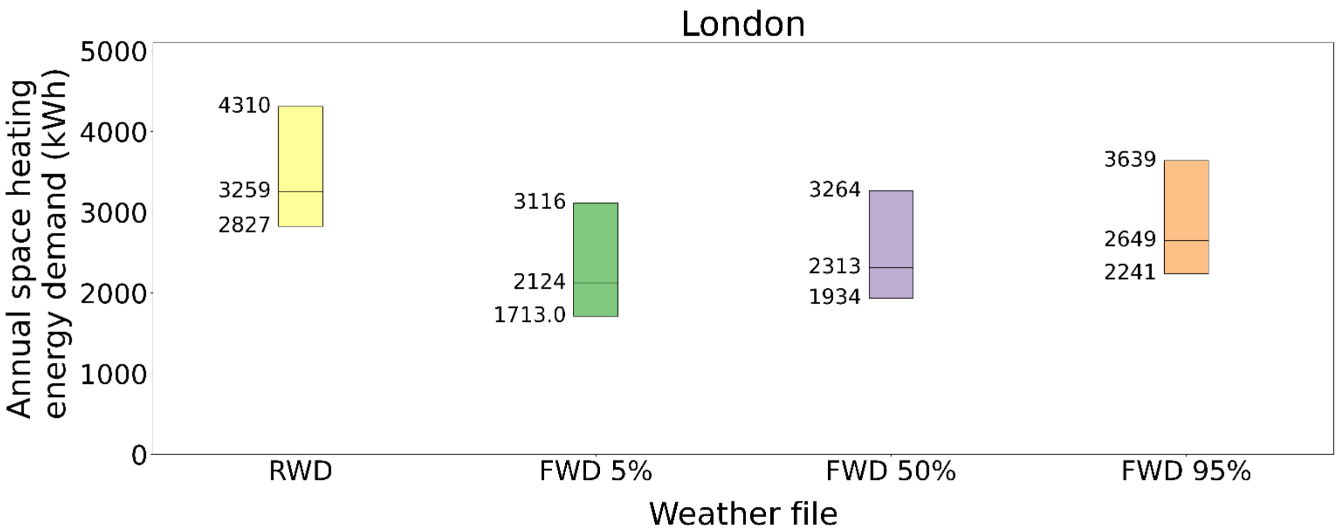


Figure 11: Annual space heating energy demand for the case-study building in Manchester.

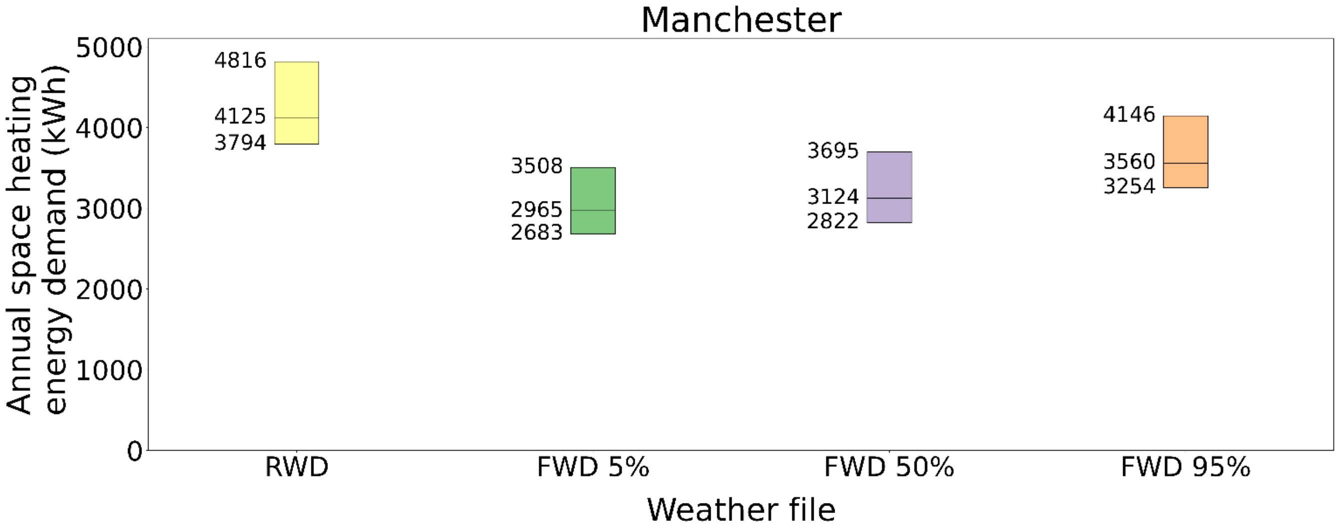
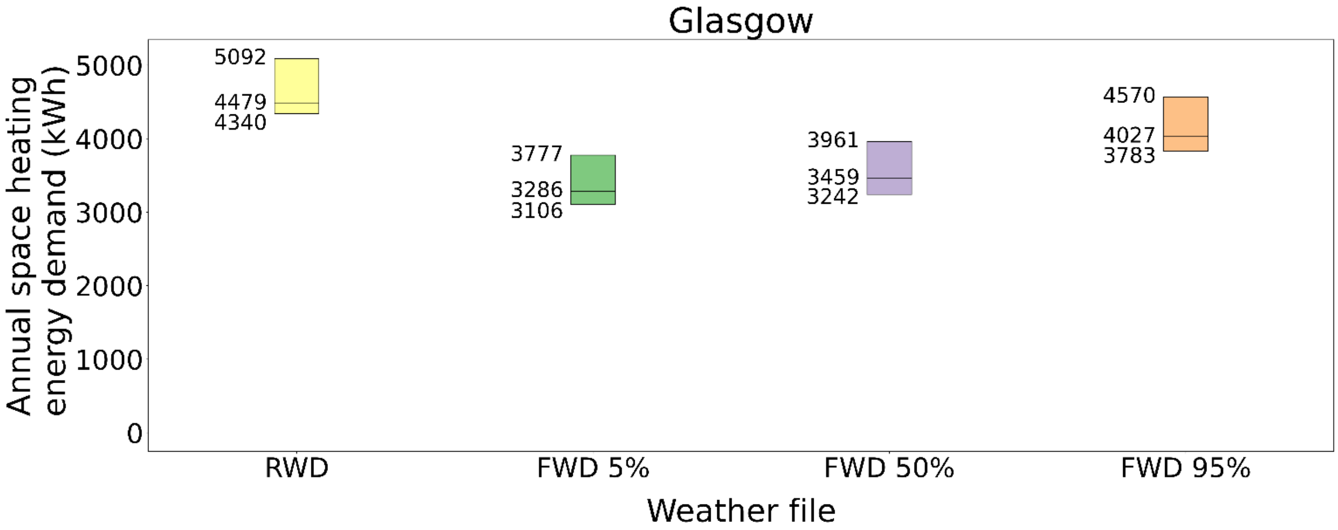


Figure 12: Annual space heating energy demand for the case-study building in Glasgow.



5.2. Overheating assessment

Figures 13-15 show the % hours of exceedance results for the case study building, from using the RWD, along with the results from the FWD (5, 50 and 95% percentiles are displayed). For simplicity, only three out of the twelve FWDs (see Section 4.2) are considered. The three chosen future weather scenarios are the ones with the mean value of hours of exceedance (%) being nearest to the 5, 50 and 95% percentiles of the mean value of hours of exceedance (%) in all future weather scenarios. The number of years in the decade that the threshold value of 3% is exceeded is shown in text.

Figure 13: TM59 criterion (% of occupied hours) for London.

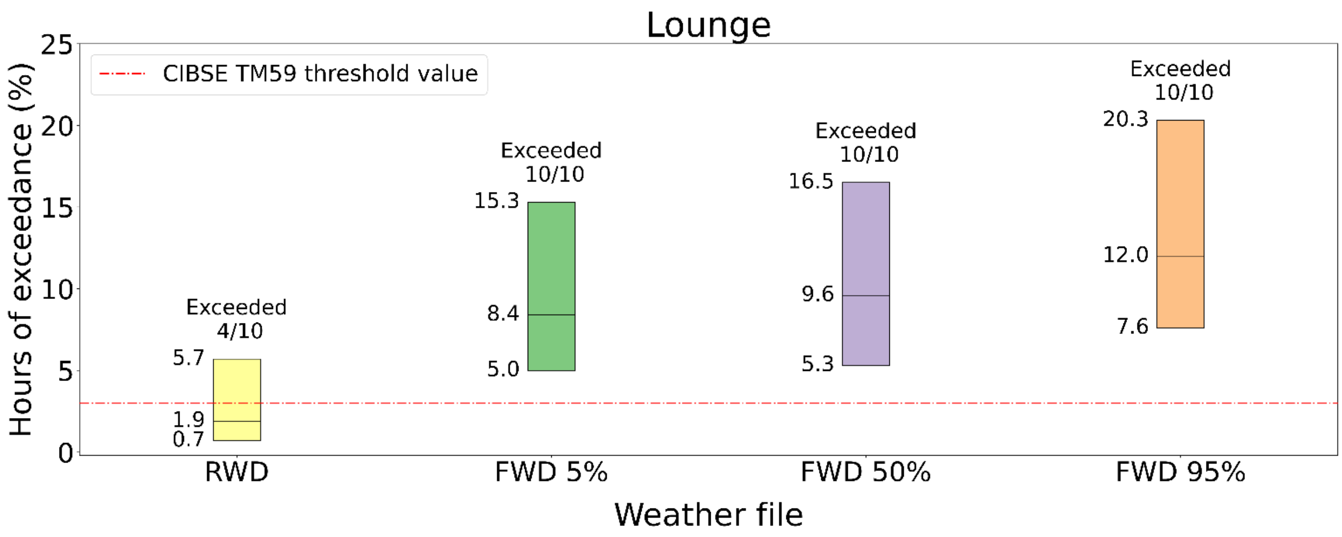


Figure 14: TM59 criterion (% of occupied hours) for Manchester.

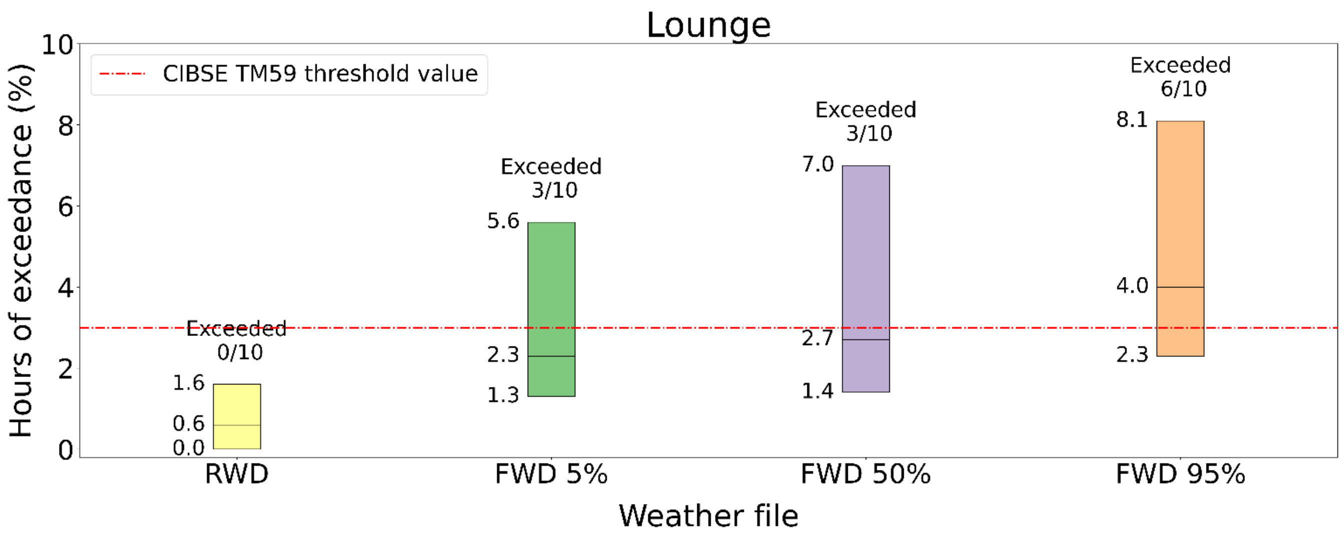
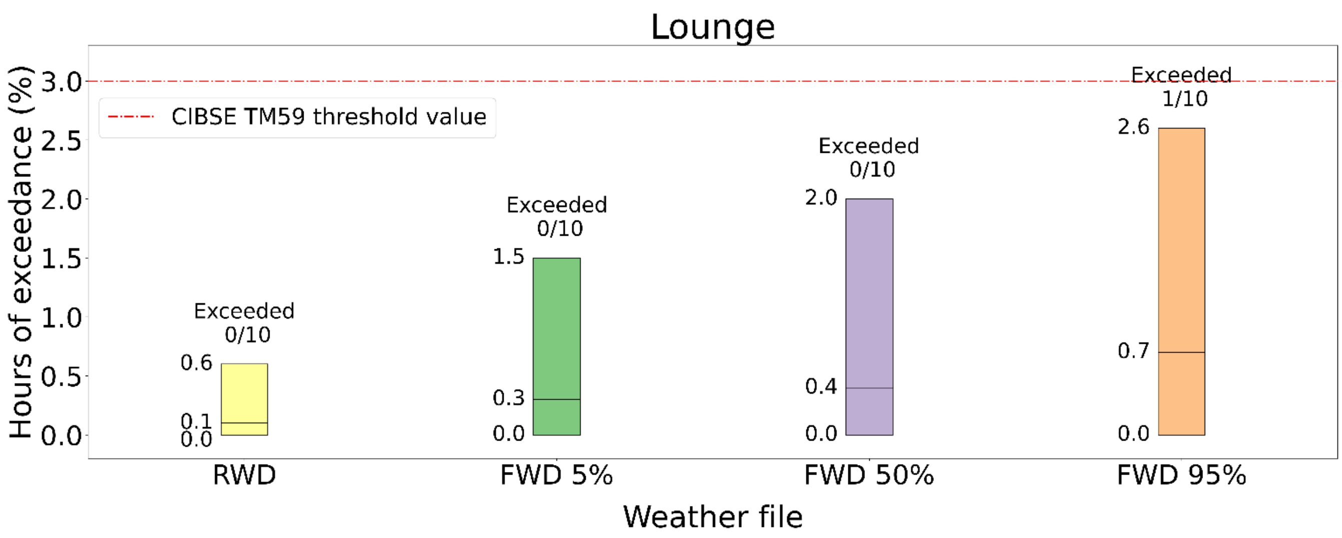


Figure 15: TM59 criterion (% of occupied hours) for Glasgow.



6. Discussion and conclusions

It is well-known that the annual energy demand for space heating a home is driven by the weather. Similarly, overheating in summer is weather dependent. The use of weather files from different geographical locations is well established in building simulation. However, the effects of annual variation and our changing climate are usually ignored. This work shows that these variations are significant.

This report recommends that a single weather file for all types of building simulations should be used, to overcome these difficulties and to facilitate the simultaneous assessment of energy, overheating and hygrothermal performance of a building. This weather file would contain data from the previous ten years (2010-2019) of weather and is therefore called the Recent Weather Decade (RWD). Future weather decade (FWD) files for the 2060s can then be obtained by morphing the RWDs using existing techniques.

The introduction of this recent weather decade (RWD) file for building simulation negates the need to create unrealistic weather files using observations from different years to try and represent an average or extreme. By using the most recent ten years, RWDs capture the changing weather, and especially the recent spate of heat waves experienced in UK summers. A potential drawback of these files is that the computational load increases by a factor of 10 in the case of the RWD files and by a factor of 30 in the case of the FWD files (since three scenarios have to be assessed). Nevertheless, advances in computing power mean that simulating a building over ten years, rather than one, is unproblematic although it might be an issue in large optimisation studies.

The results of simulating the case study building in London, Manchester and Glasgow show the benefits of this new approach. Figures for energy demand and overheating can still be averaged over the ten years if a single outcome is desired, but the results from all ten years provide a valuable range of outcomes without the need for more complex probabilistic modelling. Understanding the results is intuitive – we understand that the weather varied over the last decade much better than we might understand uncertainty and Monte-Carlo simulation.

The use of RWDs will also be appropriate to hygrothermal modelling to understand moisture risk. Hygrothermal models are typically run for many years, as moisture transport in buildings is slow compared with heat transfer. A real decade of weather is arguably preferable to repeating a single year – the real variability is maintained, rather than repeating a particularly wet year, for example. Long term changes in patterns of rainfall are captured by using the most recent decade of weather.

Morphing the RWD to create future weather decade (FWD) scenarios is relatively straightforward and preserves the relationship to today's weather. The use of the 5th, 50th and 95th percentile results, each based on a morphed decade of weather data, helps illustrate the uncertainty as a range of potential outcomes.

The RWD and FWD files developed in this research improved the accuracy, and increased the insight gained, from the modelling work in the DEEP project. More specifically, the RWD files were employed in the work presented in two subsequent DEEP reports: ‘DEEP report 6.04’ [39] and ‘DEEP report 6.03’ [40] associated with the assessment of overheating and hygrothermal performance respectively of retrofitted homes within the context of the DEEP project. It is hoped that they will be useful beyond this project as well.

Future work to develop the RWD files could consider the use of solar data from alternative sources e.g., from the Copernicus Atmosphere Monitoring Service (CAMS) radiation service [1] and observe whether this improves the weather files or not. Consideration should also be given to leap years and whether or not to include the extra day of data from these years as some software (e.g. Wufi hygrothermal simulation) does not accept 366 days in a year. For the FWD files, different or additional time periods to the predictions for 2051 to 2070 used here could be considered. For both RWD files and FWD files, the representation of the Urban Heat Island (UHI) may not be well-represented in the current weather files and this should be explored further as it may be important for overheating assessment. Finally, both RWD files and FWD files should be tested in various housing types.

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Appendix A: Weather analysis for RWD

This section provides a comparison between the RWD, TRY and DSY and three metrics derived from them; Heating Degree Days (HDD), Cooling Degree Hours (SWCDH), and Wind Driven Rain (WDR). These metrics provide some indication of the impact of the examined climate on the energy, overheating and hygrothermal performance of a building. The comparison was performed for three different locations; London (51.51°,-0.13°) Manchester (53.48°,-2.24°) and Glasgow (55.87°, -4.26°). These three locations do not only differ significantly geographically, but also in terms of the exposure zone that they belong to in the Wind Driven Rain Exposure Map. London belongs in category 1 (Sheltered), Manchester belongs to category 2 (Moderate) and Glasgow belongs to category 3 (Severe) [41]. Because the above locations are not in the middle of the bounding box[17], the adjacent boxes were considered as well by selecting the interpolation option (where an Inverse Distance Weighting Interpolation is performed) in the Shiny Weather Data application (Section 3).

The TRY (which is a representative year of the years 2010-2019 that constitute the RWD) was created using the Finkelstein–Schafer (FS) statistical method [42] and following the methodology described in BS EN ISO 15927 [43]. Synoptically, representative individual months were chosen from the analysed database based primarily on air temperature, humidity and solar radiation, and secondarily on wind speed. The DSY files were created by collecting the data from the ERA5 database again for the individual years that were chosen by CIBSE to reflect a moderately warm summer suitable to be used in an overheating assessment [8].

Table A.1 Details of the files used in the weather analysis.

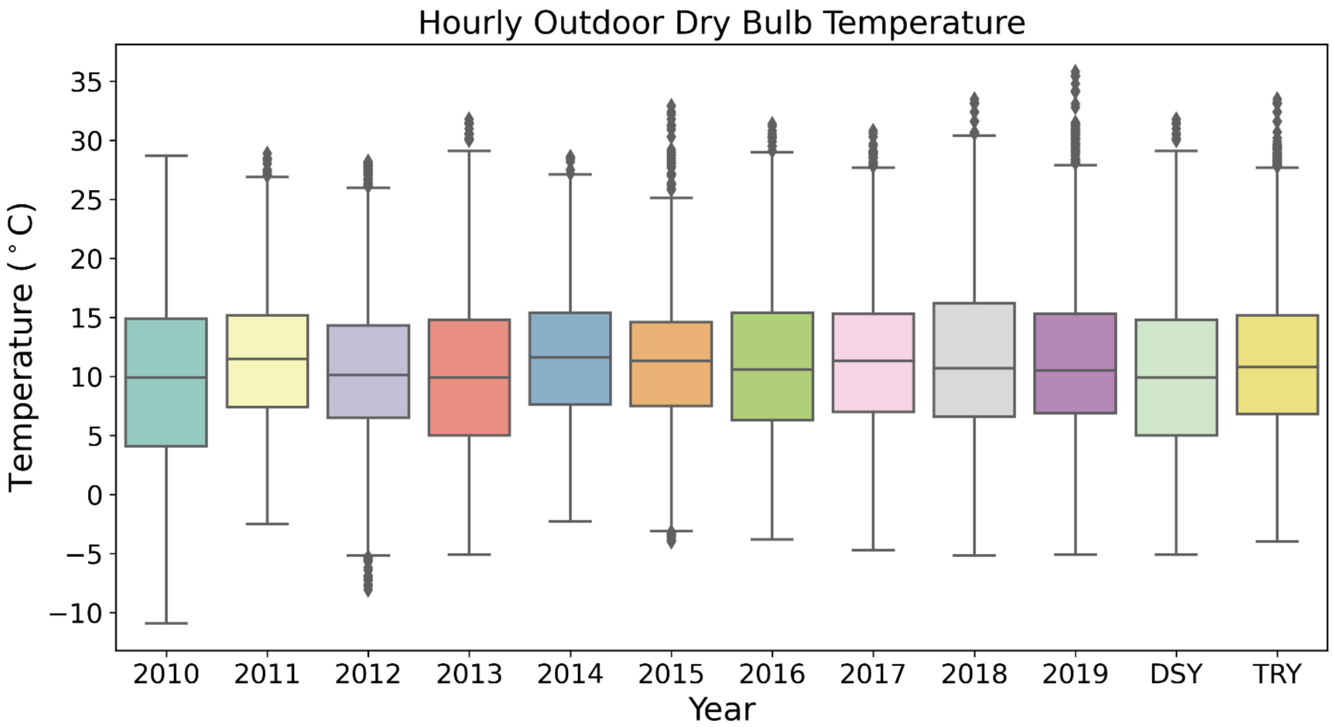
Location	Weather file	Type	Years	Source of weather data
London	RWD	Multiple year file	2010-2019	ERA5 database
	TRY	Single year file		
	DSY		2013	
Manchester	RWD	Multiple year file	2010-2019	ERA5 database
	TRY	Single year file		
	DSY		1997	
Glasgow	RWD	Multiple year file	2010-2019	ERA5 database
	TRY	Single year file		
	DSY		2003	

[17] ERA5 database as mentioned in Section 3 provide values of weather parameters over an area that equals to 0.25° x 0.25°.

London

Figures A.1-A.4 visualise the distribution of outdoor dry bulb temperature, solar radiation, wind speed and precipitation. The box plots show the median value and the 25th (Q_1) and 75th (Q_3) percentiles[18]. The whiskers (shown in black) contain the values within the ranges $Q_1 - 1.5*IQR$ and $Q_3 + 1.5*IQR$.

Figure A.1 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in each of the examined weather files for London.



[18] Their difference is the interquartile range (IQR).

Figure A.2 Box-plot visualisation of the quartile distribution of the global horizontal radiation in each of the examined weather files for London.

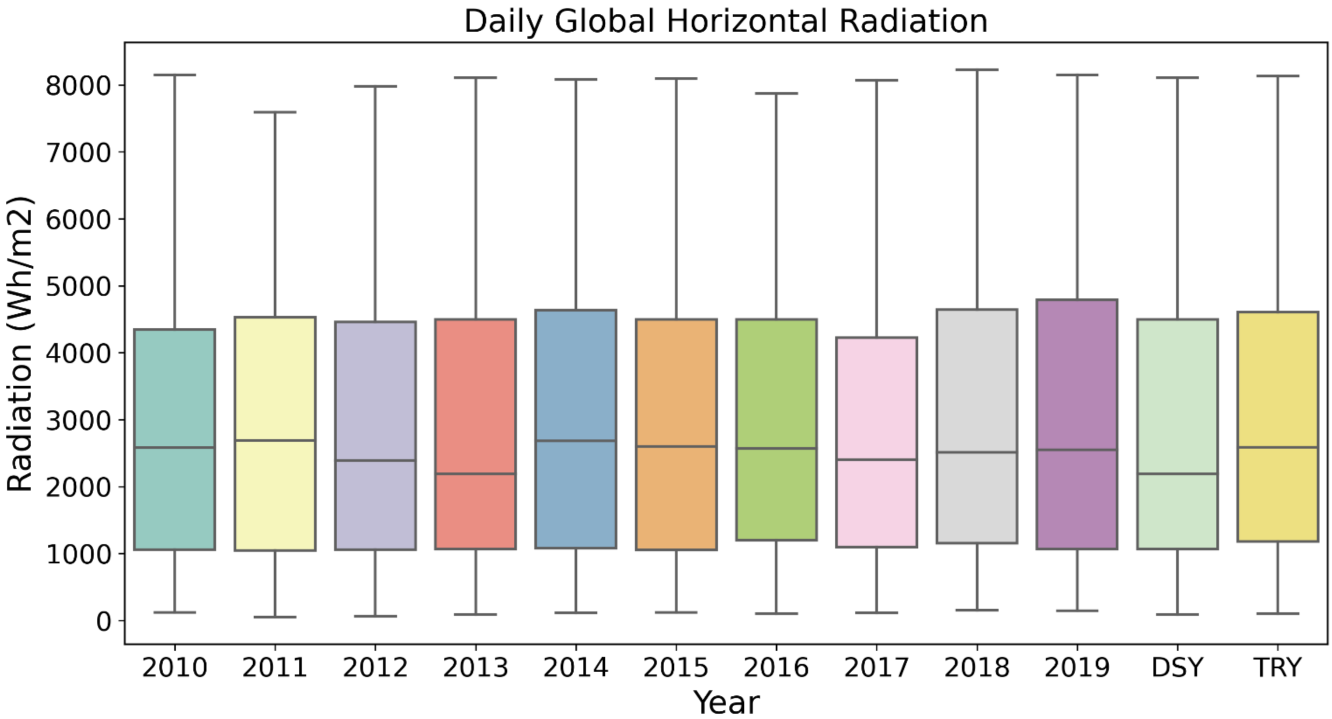


Figure A.3 Box-plot visualisation of the quartile distribution of the wind speed in each of the examined weather files for London.

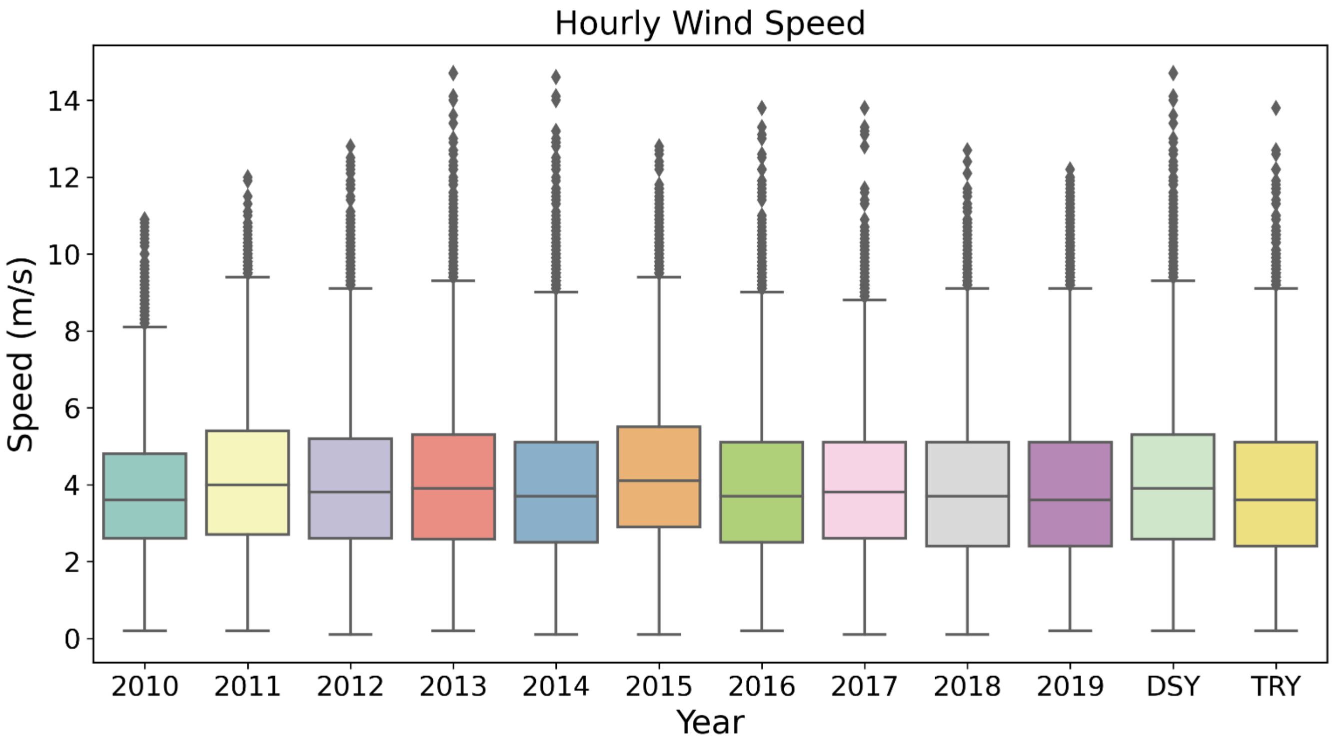


Figure A.4 Box-plot visualisation of the quartile distribution of the precipitation in each of the examined weather files for London.

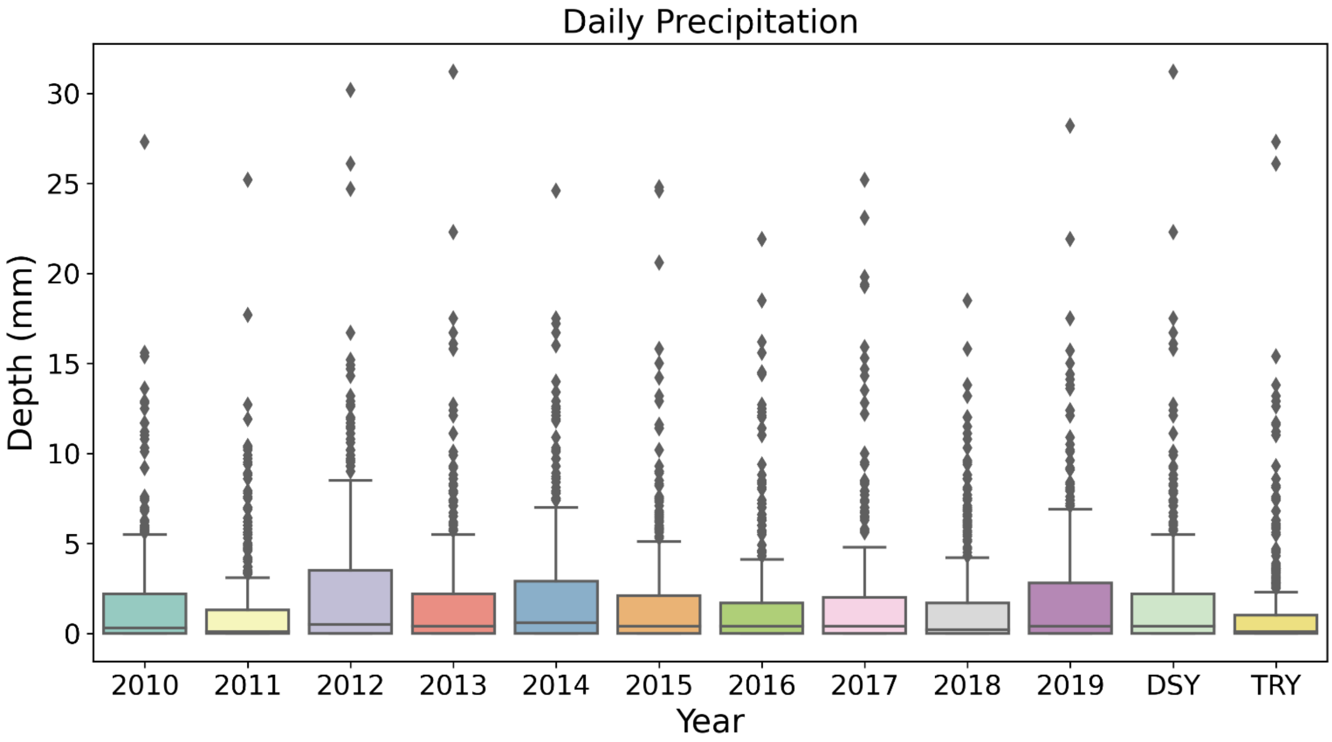


Table A.2 displays the HDD with a baseline temperature of 15°C for London for all the examined files. Within the RWD file, the HDD vary from 1558 (2014) to 2289 (2010). As it was expected the HDD in the TRY lie within this range.

Table A.2 HDD of the examined weather files for London.

Weather file	Year	HDD
RWD	2010	2289
	2011	1617
	2012	1968
	2013	2119
	2014	1558
	2015	1669
	2016	1839
	2017	1724
	2018	1800
	2019	1792
DSY	2013	2119
TRY	-	1775

Table A.3 shows the SWCDH of all the examined files. Within the RWD file the SWCDH varies from 151.6 (2014) to 2,229.1 (2019). The DSY contains the fifth largest value, which means that theoretically there are other years in the RWD that can cause more severe overheating. It is interesting that the TRY is the year with the third highest SWCDH value because it is designed to depict average weather.

Table A.3 SWCDH of the examined weather files for London.

Weather file	Year	SWCDH
RWD	2010	159.3
	2011	175.2
	2012	228.0
	2013	831.5
	2014	151.6
	2015	630.4
	2016	769.5
	2017	534.1
	2018	2089.2
	2019	2229.1
DSY	2013	831.5
TRY	-	1474.1

Table A.4 shows the WDR for all the examined files. Within the RWD file, the WDR varies from 559 (2011) to 1098 mm/h (2012). The respective value of TRY (588) is slightly larger than that of minimum value found in the RWD.

TableA.4 WDR of the examined weather files for London.

Weather file	Year	WDR
RWD	2010	669
	2011	559
	2012	1098
	2013	860
	2014	966
	2015	784
	2016	715
	2017	747
	2018	696
	2019	878
DSY	2013	860
TRY	-	588

Manchester

Figures A.5-A.8 visualise the distributions of outdoor dry bulb temperature, solar radiation, wind speed and precipitation.

Figure A.5 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in each of the examined weather files for Manchester.

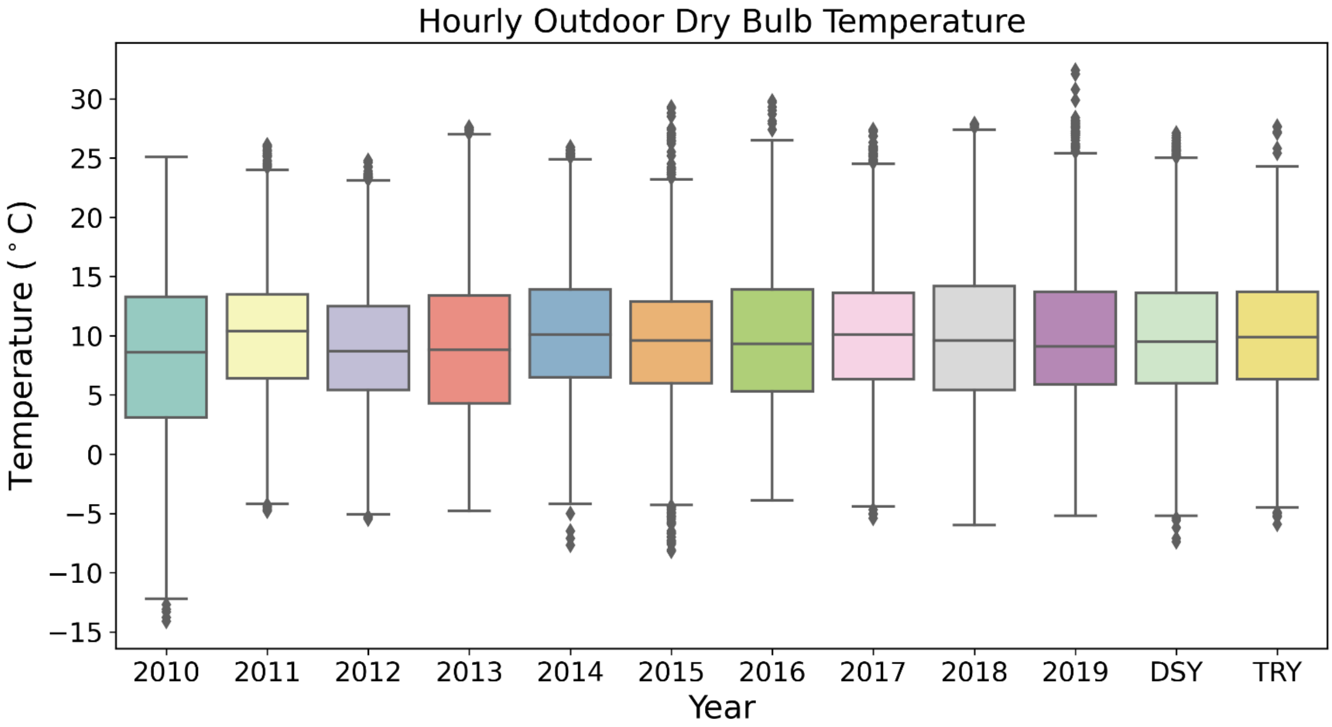


Figure A.6 Box-plot visualisation of the quartile distribution of the global horizontal radiation in each of the examined weather files for Manchester.

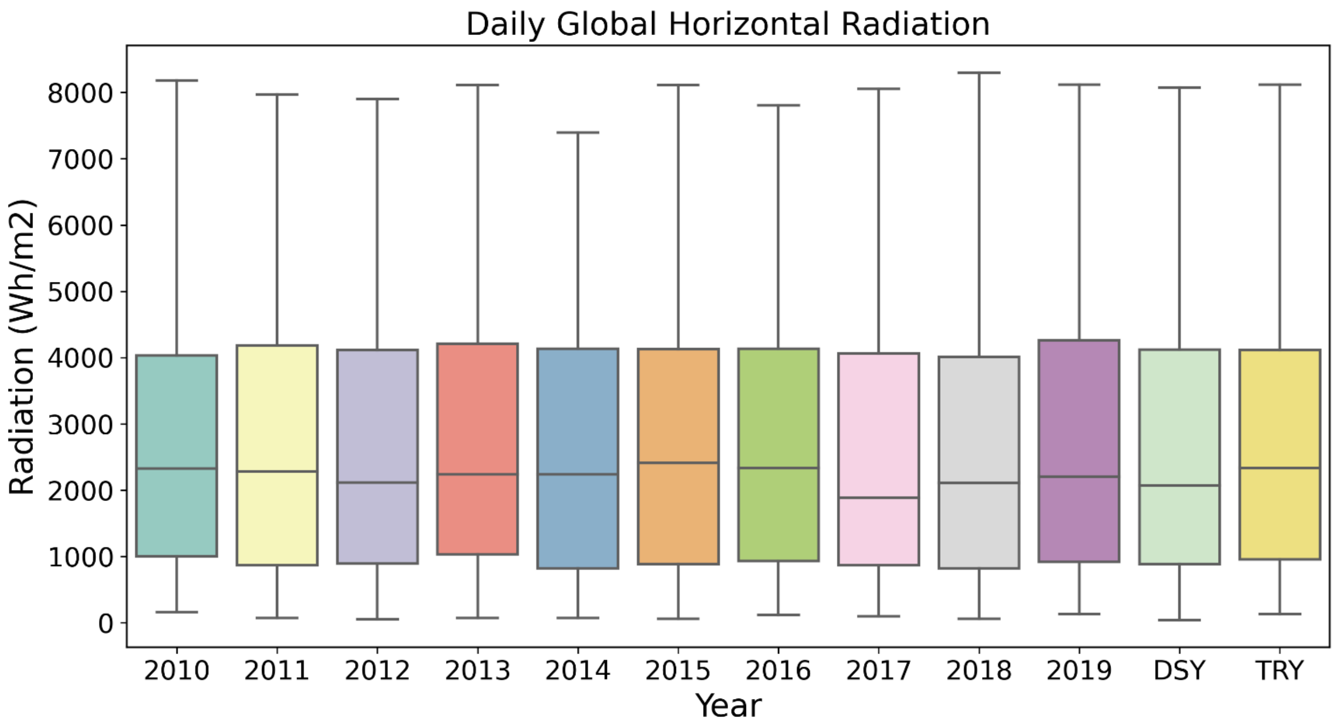


Figure A.7 Box-plot visualisation of the quartile distribution of the wind speed in each of the examined weather files for Manchester.

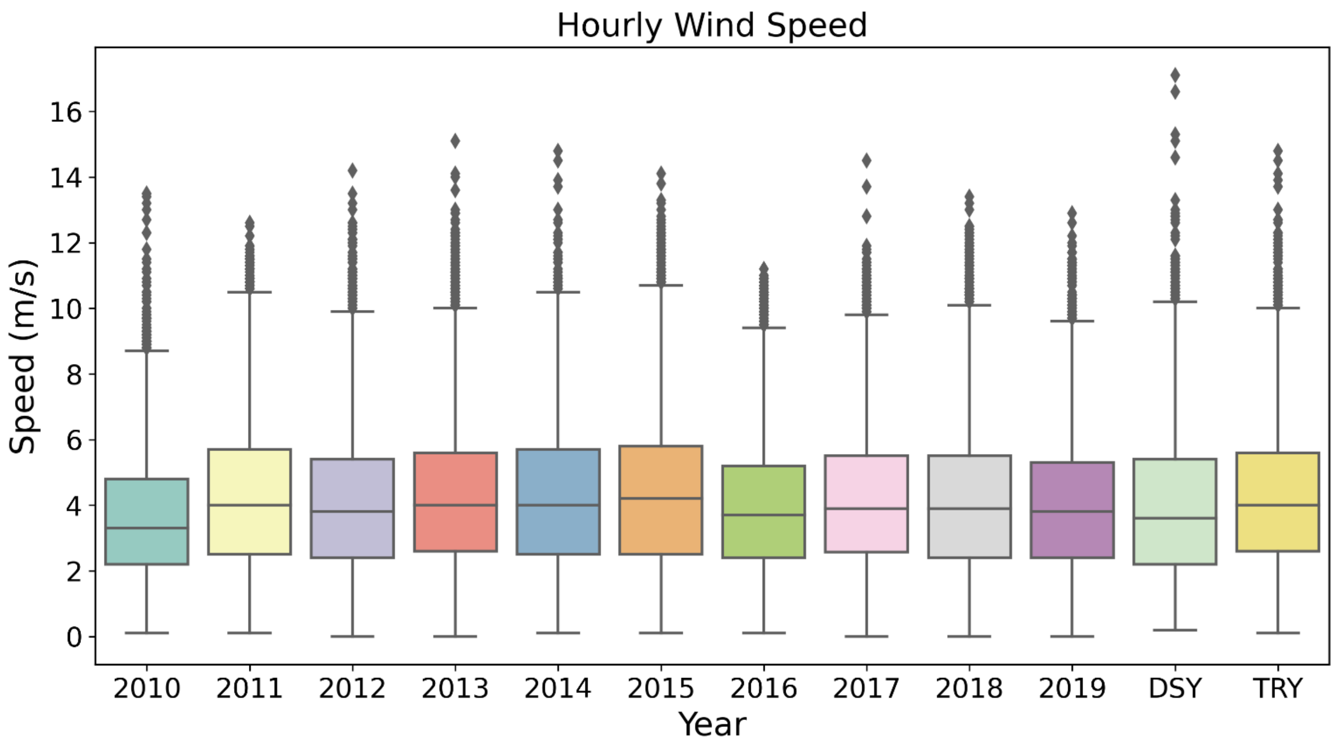


Figure A.8 Box-plot visualisation of the quartile distribution of the precipitation in each of the examined weather files for Manchester.

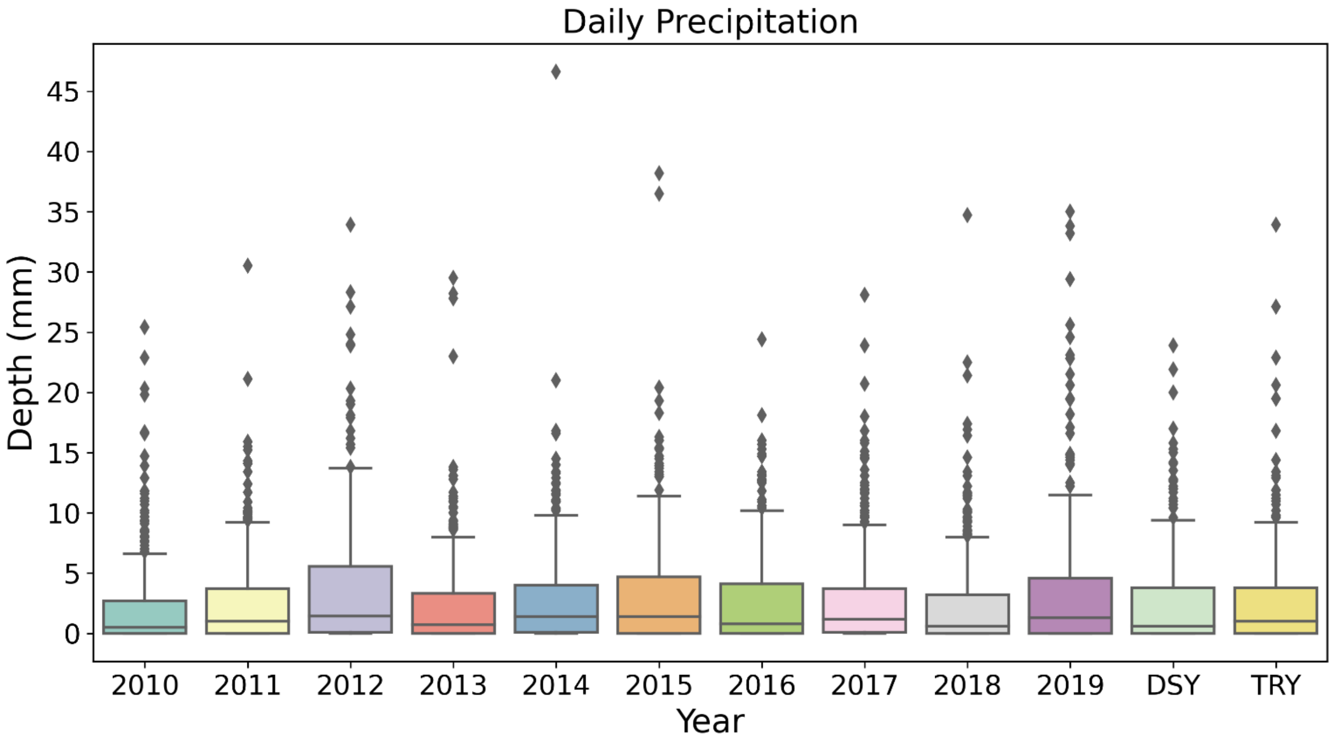


Table A.5 displays the HDD with a baseline temperature of 15°C for Manchester for all the examined files. Within the RWD file, the HDD varies from 1917 (2014) to 2651 (2010). As it was expected the HDD in the TRY (which is equal to 1978) lie within this range.

Table A.5 HDD of the examined weather files for Manchester.

Weather file	Year	HDD
RWD	2010	2651
	2011	1968
	2012	2352
	2013	2395
	2014	1917
	2015	2146
	2016	2145
	2017	2019
	2018	2133
	2019	2129
DSY	1997	2095
TRY	-	1978

Table A.6 shows the SWCDH of all the examined files. Within the RWD file, the SWCDH varies substantially; from 31.2 (2012) to 1,920.9 (2018). The DSY contains the third largest value, which means that theoretically 2018 and 2019 can cause more overheating. This time, the TRY does not contain hot weather; it is the year with the third lowest SWCDH value – demonstrating the variability.

Table A.6 SWCDH of the examined weather files for Manchester.

Weather file	Year	SWCDH
RWD	2010	104.2
	2011	355.7
	2012	31.2
	2013	914.0
	2014	441.9
	2015	599.5
	2016	776.4
	2017	523.8
	2018	1920.9
	2019	1475.6
DSY	1997	950.5
TRY	-	185.6

Table A.7 shows the WDR for all the examined files. Within the RWD file, the WDR varies from 937 (2010) to 1690 mm/h (2012). The respective value of the TRY (1287) sits roughly in the middle of this range.

Table A.7 WDR of the examined weather files for Manchester.

Weather file	Year	WDR
RWD	2010	937
	2011	1234
	2012	1690
	2013	1254
	2014	1424
	2015	1675
	2016	1247
	2017	1306
	2018	1154
	2019	1556
DSY	1997	1180
TRY	-	1287

Glasgow

Figures A.9-A.12 visualises the distribution of outdoor dry bulb temperature, solar radiation, wind speed and precipitation.

Figure A.9 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in each of the examined weather files for Glasgow.

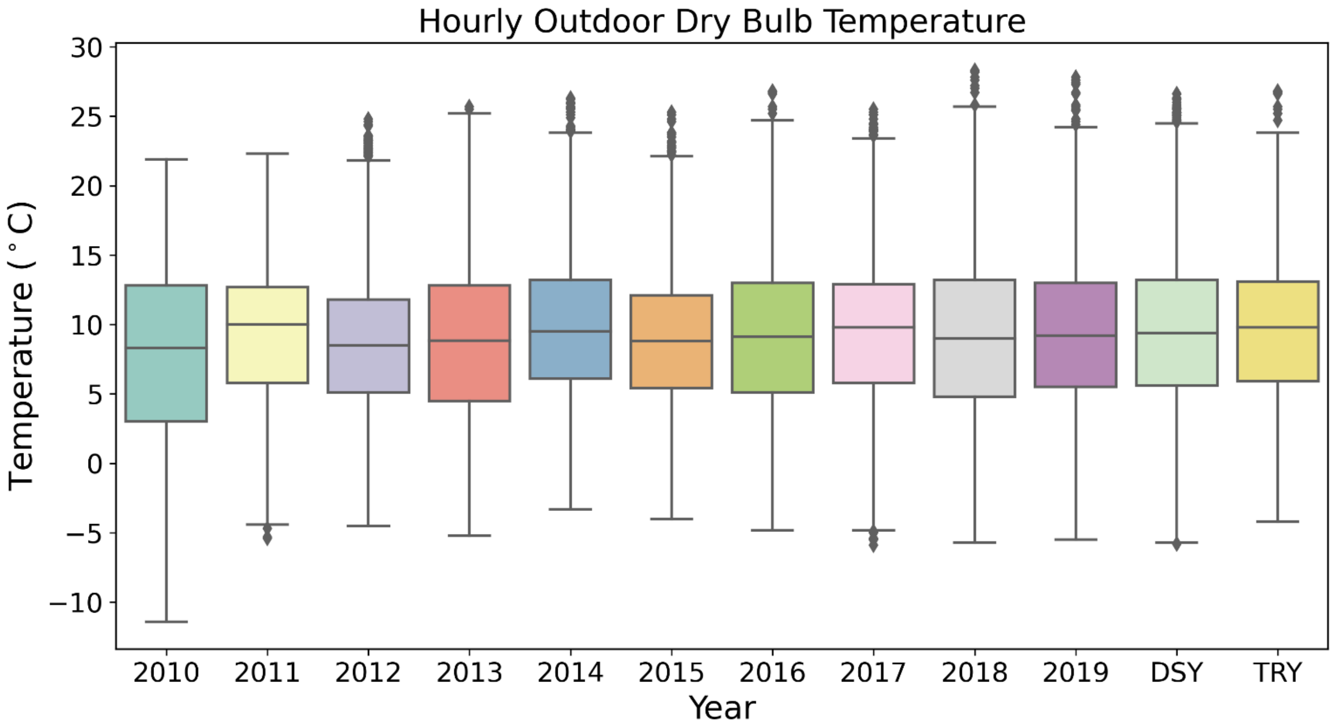


Figure A.10 Box-plot visualisation of the quartile distribution of the global horizontal radiation in each of the examined weather files for Glasgow.

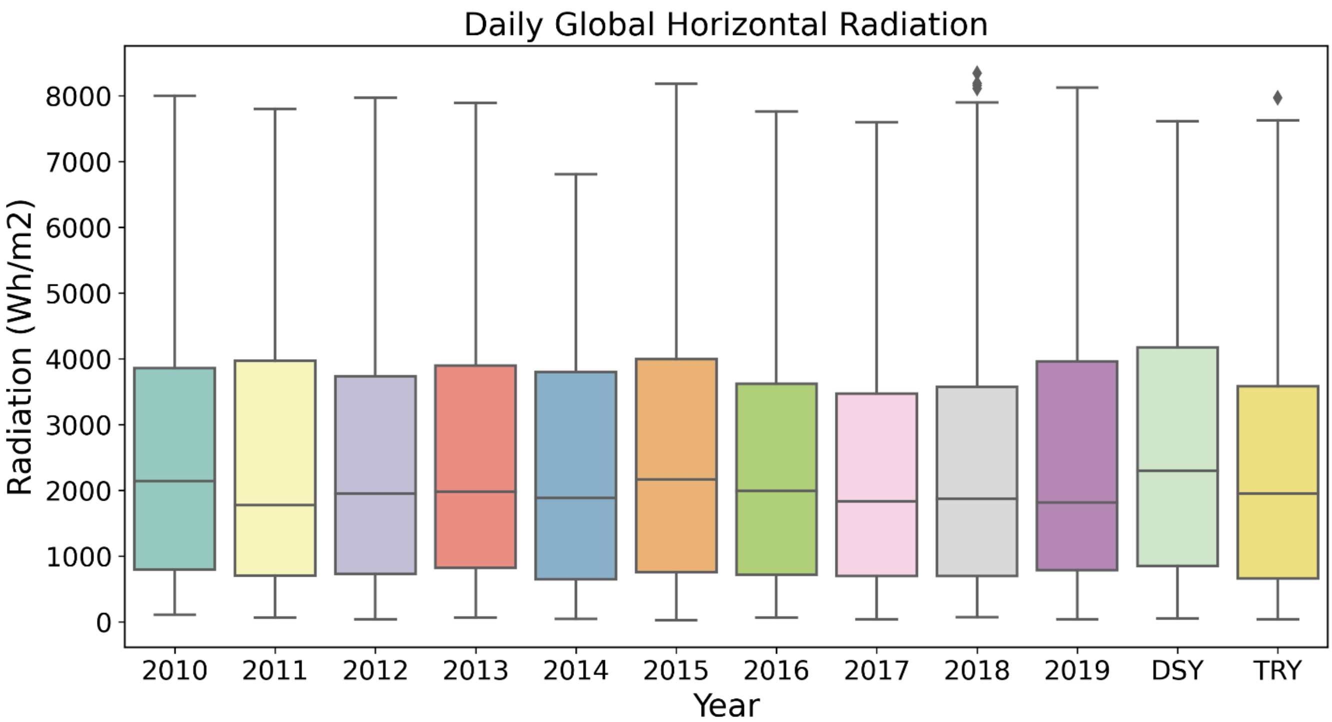


Figure A.11 Box-plot visualisation of the quartile distribution of the wind speed in each of the examined weather files for Glasgow.

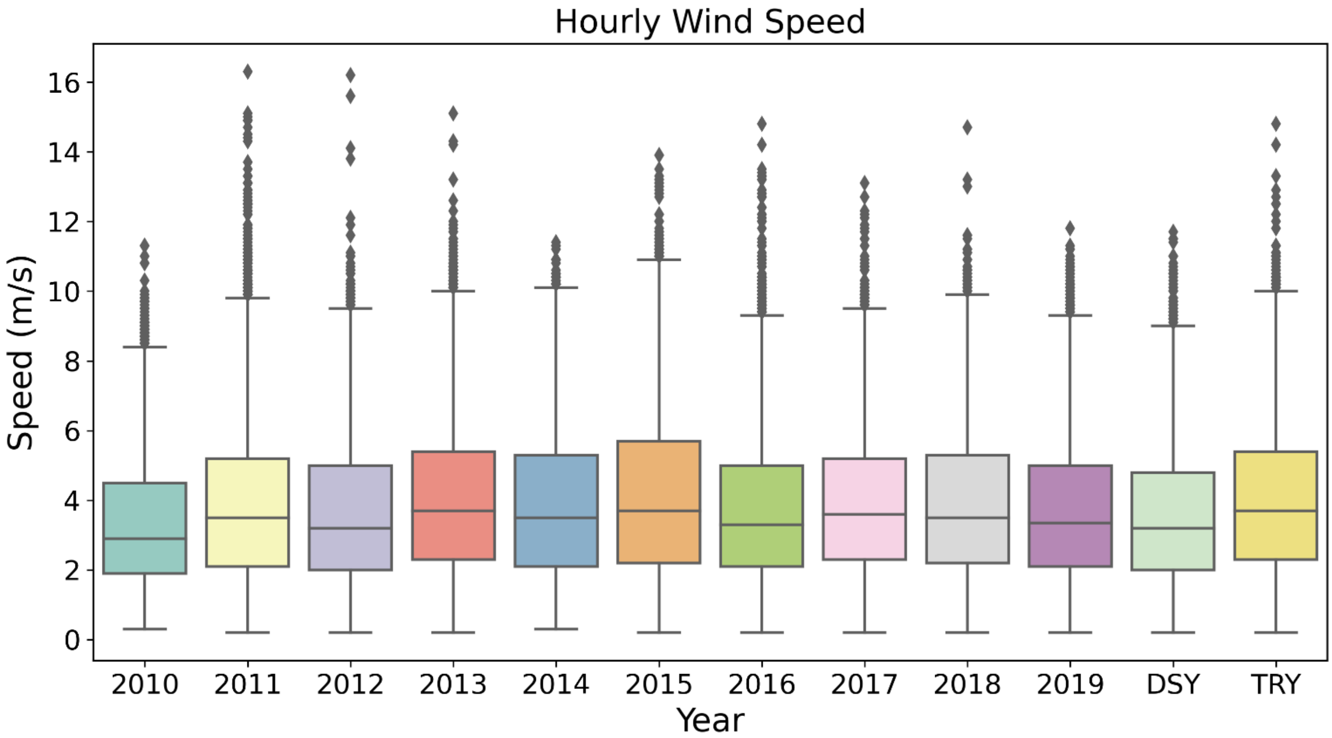


Figure A.12 Box-plot visualisation of the quartile distribution of the precipitation in each of the examined weather files for Glasgow.

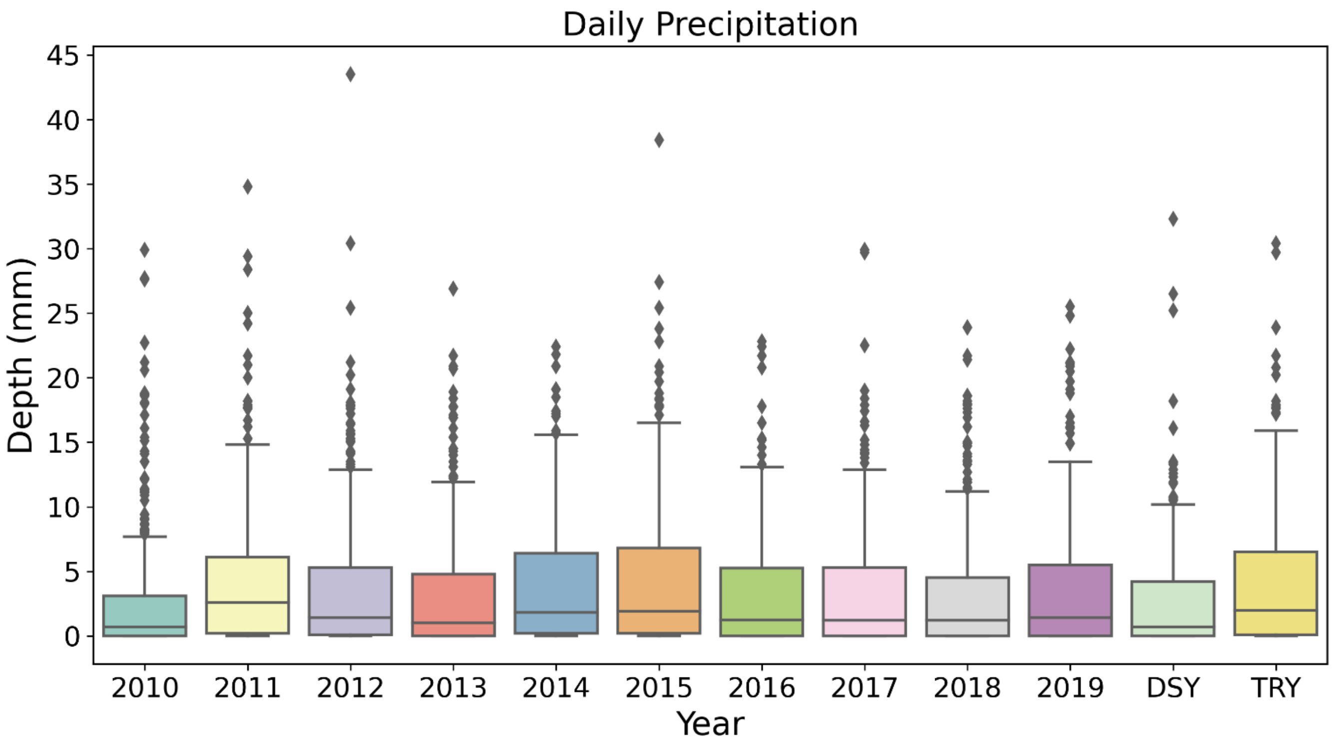


Table A.8 displays the HDD with a baseline temperature of 15°C for Glasgow for all the examined files. Within the RWD file, the HDD varies from 2049 (2014) to 2759 (2010). Again, as in the case of London and Manchester the HDD in the TRY (which is equal to 2108) lies within this range.

Table A.8 HDD of the examined weather files for Glasgow.

Weather file	Year	HDD
RWD	2010	2759
	2011	2124
	2012	2446
	2013	2404
	2014	2049
	2015	2330
	2016	2283
	2017	2156
	2018	2319
	2019	2242
DSY	2003	2224
TRY	-	2108

Table A.9 shows the SWCDH of all the examined files. Within the RWD file, the SWCDH varies dramatically; from 0.2 (2012) to 700.8 (2018). This time, the DSY contains the largest value, meaning that theoretically no single year within the RWD can cause more severe overheating than the DSY. Finally, the TRY is the year with the seventh highest SWCDH value.

Table A.9 SWCDH of the examined weather files for Glasgow.

Weather file	Year	SWCDH
RWD	2010	0.9
	2011	11.5
	2012	0.2
	2013	357.2
	2014	399.7
	2015	123.8
	2016	239.9
	2017	57.4
	2018	700.8
	2019	517.5
DSY	2003	899.0
TRY	-	214.3

Table A.10 shows the WDR for all the examined files. Within the RWD file, the WDR varies from 1141 (2010) to 2216 mm/h (2015). The respective value of the TRY (1902) sits towards the high end of this range.

Table A.10 WDR of the examined weather files for Glasgow.

Weather file	Year	WDR
RWD	2010	1141
	2011	1892
	2012	1549
	2013	1495
	2014	1751
	2015	2216
	2016	1419
	2017	1358
	2018	1432
	2019	1403
DSY	2003	1125
TRY	-	1902

Appendix B: Case study flat input data

Table B.1 Thermal properties of case study flat.

Element	U-value (W/(m²·K))	Glazing visible transmittance	Infiltration (ach)
Exterior wall	1.76		0.48
Exterior glazing	2.72	0.81	

Table B.2 Gains from occupants, equipment and lights obtained from NCM database.

Zone	People per floor area (person/m²)	Activity level (W)	Lighting level (W/m²)	Electric equipment level (W/m²)
Living room	1.88E-02	110	1.88	3.9
Kitchen	2.37E-02	160	3.75	30.28
Bedroom	2.29E-02	90	1.25	3.58

Table B.3 Hourly fractions for occupancy, equipment and lights from NCM database.

	Occupancy			Equipment			Lights		
Hour	Living room	Kitchen	Bedroom	Living room	Kitchen	Bedroom	Living room	Kitchen	Bedroom
1	0	0	1	0.06	0.066052	0.06993	0	0	0
2	0	0	1	0.06	0.066052	0.06993	0	0	0
3	0	0	1	0.06	0.066052	0.06993	0	0	0
4	0	0	1	0.06	0.066052	0.06993	0	0	0
5	0	0	1	0.06	0.066052	0.06993	0	0	0
6	0	0	1	0.06	0.066052	0.06993	0	0	0
7	0	0	1	0.06	0.07	0.07	0	0	0
8	0	0	0.5	0.06	0.07	0.53	0	0	0
9	0	0	0.25	0.06	0.07	1	0	0	0
10	0	1	0.25	0.06	1	0.53	0	1	1
11	0	1	0.25	0.06	1	0.53	0	1	1
12	0	1	0.25	0.06	1	0.53	0	1	1
13	0	1	0.25	0.06	1	0.53	0	1	1
14	0	1	0.25	0.06	1	0.53	0	1	1
15	0	1	0.25	0.06	1	0.53	0	1	1
16	0	1	0.25	0.06	1	0.53	0	1	1
17	0	1	0.25	0.06	1	0.07	0	1	1
18	0.5	1	0.25	0.53	1	0.30	0	1	1
19	0.5	0	0.25	0.53	0.07	0.53	0	0	0
20	0.5	0	0.25	0.53	0.07	0.77	0	0	0
21	0.5	0	0.25	0.53	0.07	0.77	0	0	0
22	1	0	0	1	0.07	1	0	0	0
23	0.67	0.2	0.25	0.69	0.25	0.77	1	1	0.2
24	0	0	0.75	0.06	0.07	0.30	0	0	0

Appendix C: Morphing the RWD

This section presents the detailed equations employed in the morphing of the RWD.

Shift and stretch algorithm

Dry bulb temperature is obtained through a shift and stretch transformation as follows:

$$db_t = db_{to} + \Delta_{xm} + a_m*(db_{to} - db_{to[m]})$$ Equation C.1

where,

db_t is the morphed dry bulb temperature (°C)
db_{to} is the dry bulb temperature (°C) of the baseline weather period (i.e., the RWD)
Δ_{xm} is the difference of the monthly mean dry bulb temperature (°C) between the baseline and future weather periods
$db_{to[m]}$ is the monthly mean dry bulb temperature (°C) of the baseline weather period (i.e., the RWD)
a_m is a scaling factor calculated from the following equation:

$$a_m = (\Delta TMAX_m - \Delta TMIN_m) / ([db_{tomax}]_m - [db_{tomin}]_m)$$ Equation C.2

where,

$\Delta TMAX_m$ is the difference of the monthly average daily maximum dry bulb temperature between the baseline and future weather periods
$\Delta TMIN_m$ is the difference of the monthly average daily minimum dry bulb temperature m (°C) between the baseline and future weather periods
$[db_{tomax}]_m$ is the monthly average daily maximum dry bulb temperature of the present weather file (°C)
$[db_{tomin}]_m$ is the monthly average daily minimum dry bulb temperature of the present weather file (°C)

Stretch algorithm

Relative humidity, atmospheric pressure, solar radiation, wind speed and rain are obtained through a stretch algorithm as follows:

$$X_t = X_{to}*a_m$$ Equation C.3

where,

X_t is the morphed hourly value of each one of the above weather parameters
X_{to} is the monthly mean value of the present weather file of each one of the above parameters

a_m is the monthly stretch factor given by the following equation:

$$a_m = 1 + \Delta x_m / X_{to} \quad \text{Equation C.4}$$

where,

Δx_m is the difference of the monthly mean value between the baseline and future weather periods

In the case of solar radiation, it should be noted that only the global radiation is morphed; UKCP18 does not provide predictions for the direct and diffuse components of it. These have been derived using the morphed global radiation Skartveit and Olseth separation model; a model that literature has shown performs very well in comparison to other separation models and especially to the Cloud Radiation Model (CRM) which is implemented in the CIBSE weather files [7].

Shift algorithm

Total cloud cover and rain have been morphed using a shift transformation as follows:

$$X_t = X_{to} + \Delta x_m \quad \text{Equation C.5}$$

Regarding atmospheric pressure, the baseline period contains the station pressure while UKCP18 provides projections for the mean sea level pressure. Hence, Δx_m has been adjusted taking into account the height above sea level (m) and air temperature (°C) of the considered location employing the equation below:

$$\Delta x_{m(adjusted)} = \Delta x_m \left(1 - 0.0065 * h / (db_t + 0.0065 * h + 273.15)\right)^{-5.257} \text{[19]} \quad \text{Equation C.6}$$

where,

h is the height above sea of the considered location (m)

db_t is the outdoor air temperature

[19] The equation comes from World Meteorological Organization.

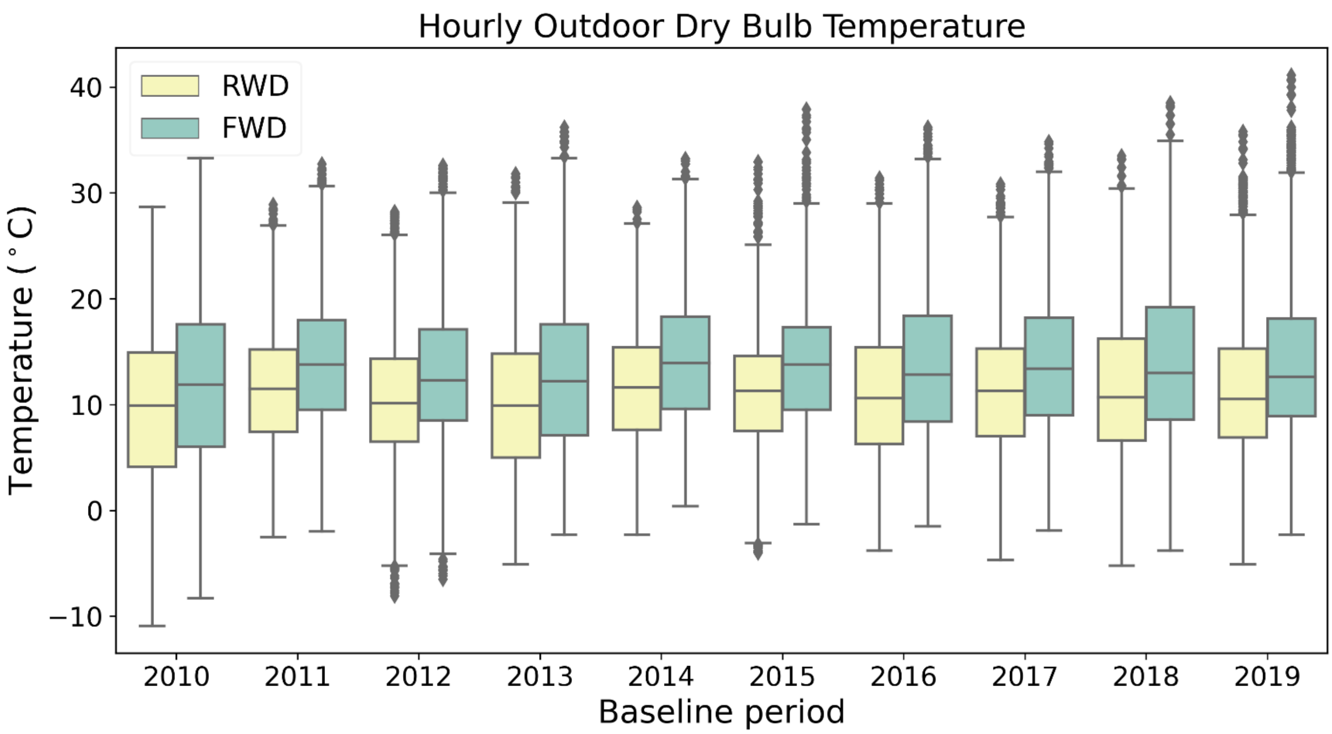
Appendix D: Comparison between RWD and FWD

This section provides a comparison between the RWD files analysed in Appendix A and their corresponding FWD files considering uncertainty in the future weather in the form of twelve different scenarios. The analysis was conducted using the same locations and metrics as in Appendix A. For the FWDs, the median[20] future weather scenario is illustrated.

London

Figures D.1-D.3 display outdoor dry bulb temperature, global solar radiation and precipitation for both the RWD as well as its morphed, FWD, file. It can be seen that for all the years within the baseline period (i.e., 2010-2019) outdoor dry bulb temperature and global solar radiation are higher in the FWD than in the RWD. The opposite trend is noticed for precipitation (with the exception of 2016); the future period is dryer than the current one. Nevertheless, this observation concerns the future weather scenario that corresponds to the median future weather scenario; some future scenarios are more wet in comparison to the current baseline.

Figure D.1 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the RWD and FWD for London.



[20] This is the nearest scenario to the 50% percentile of the mean values of the weather parameter considered.

Figure D.2 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the RWD and FWD for London.

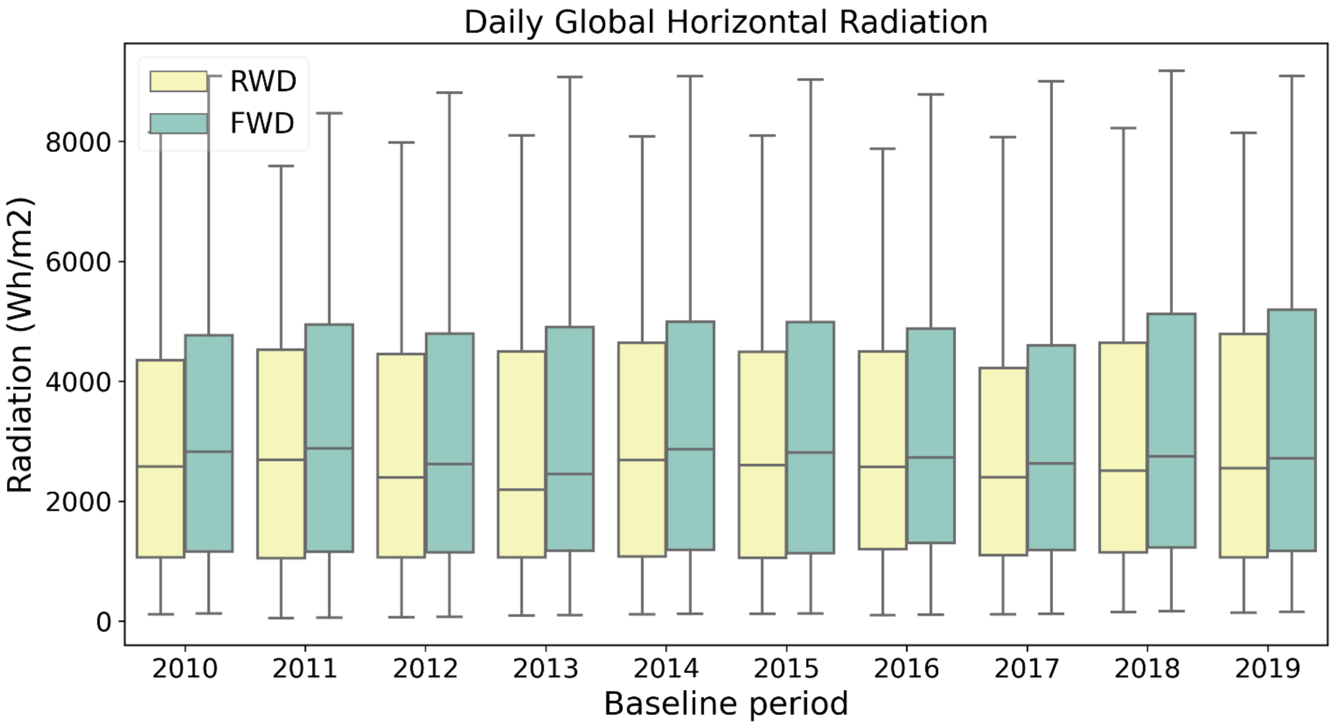
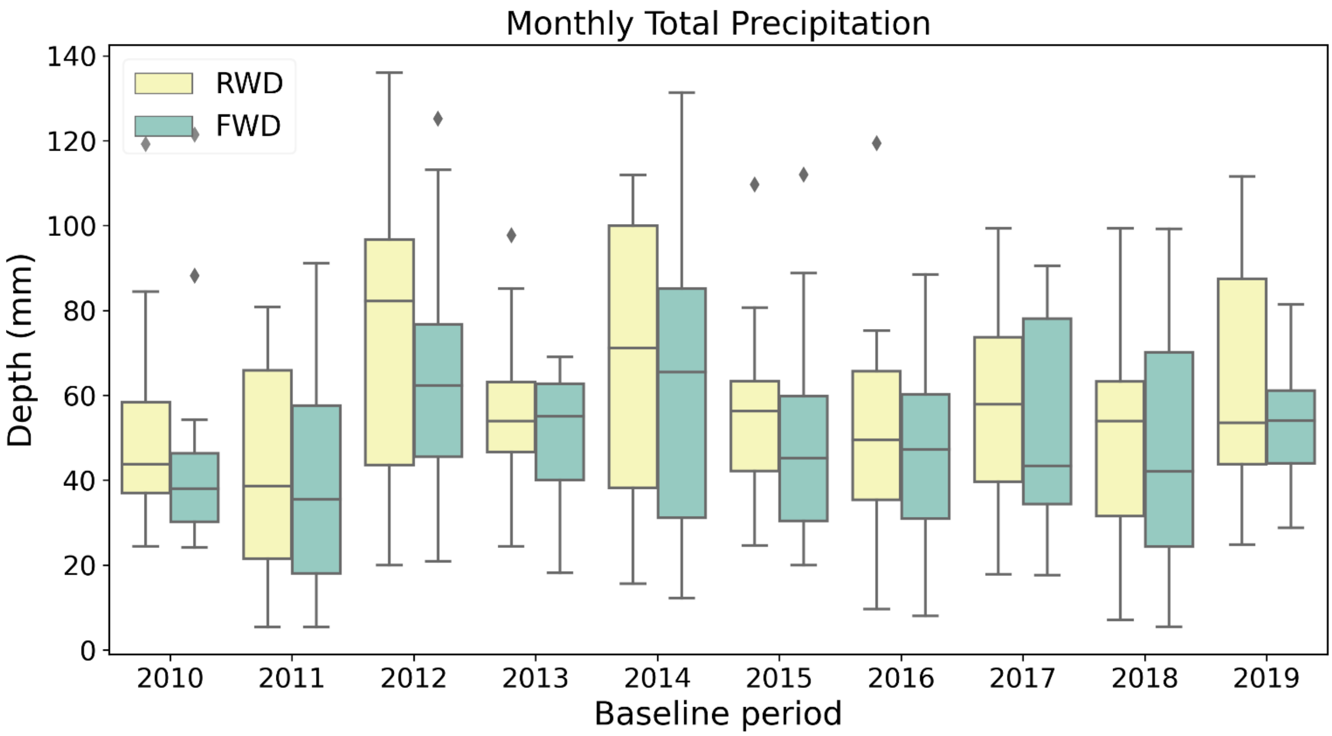


Figure D.3 Box-plot visualisation of the quartile distribution of the precipitation in the RWD and FWD for London.



Figures D.4 and D.5 show daily outdoor temperature and hourly global radiation as well as direct normal and diffuse radiation In Figure D.4it can be seen that the main effect of morphing is to shift vertically the temperature values of the original file.

Figure D.4 Daily outdoor temperature considering future weather scenario 5 for London.

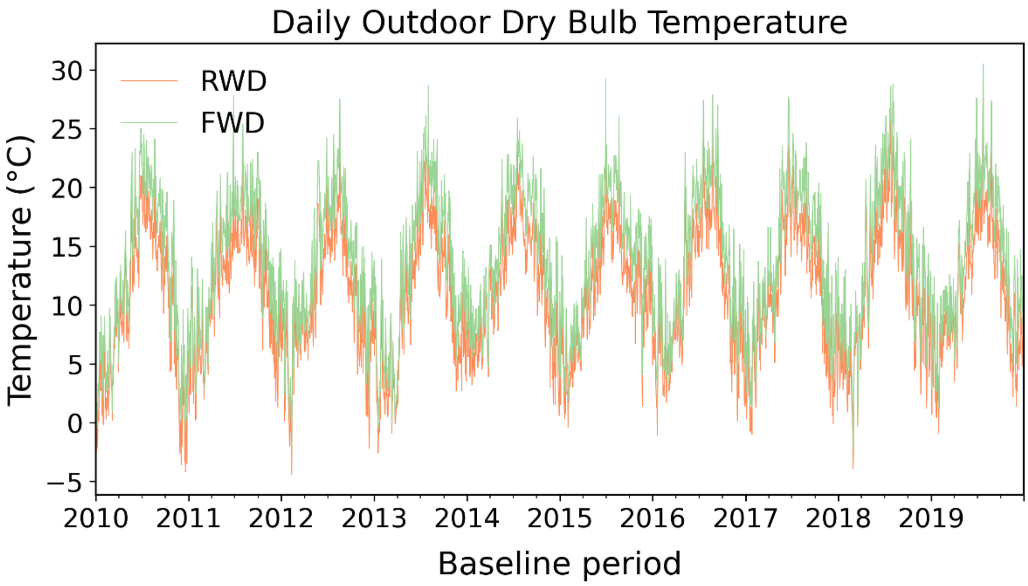
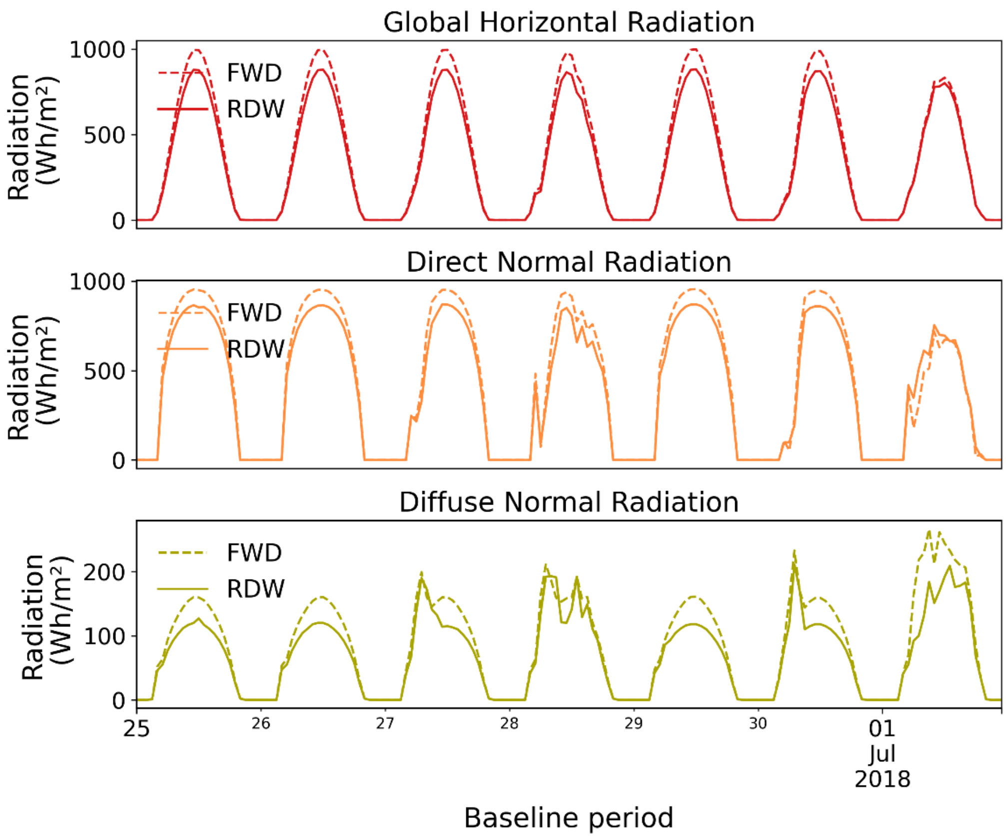


Figure D.5 Global, direct normal and diffuse solar radiation for London during a typical week in summer.



Figures D.6-D.8 show a comparison between the RWD file and its morphed one considering the following metrics; HDD, SWCDH and WDR.

Figure D.6 HDD for the RWD and FWD (including the values of all the assessed future scenarios) for London.

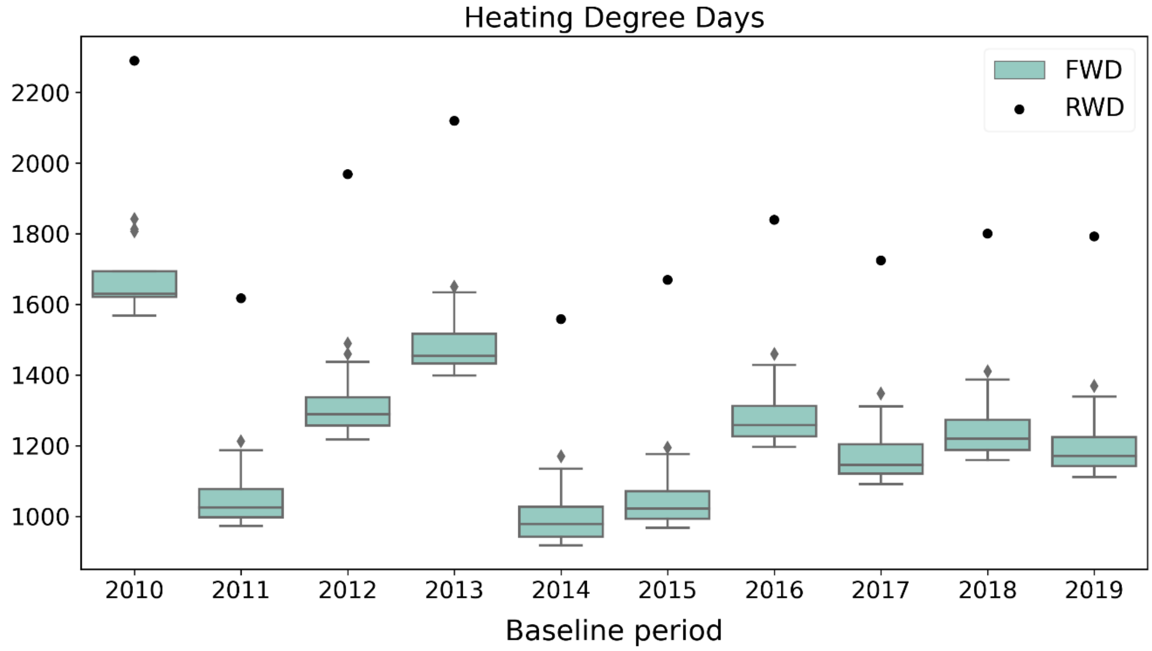


Figure D.7 SWCDH for the RWD and FWD (including the values of all the assessed future scenarios) for London.

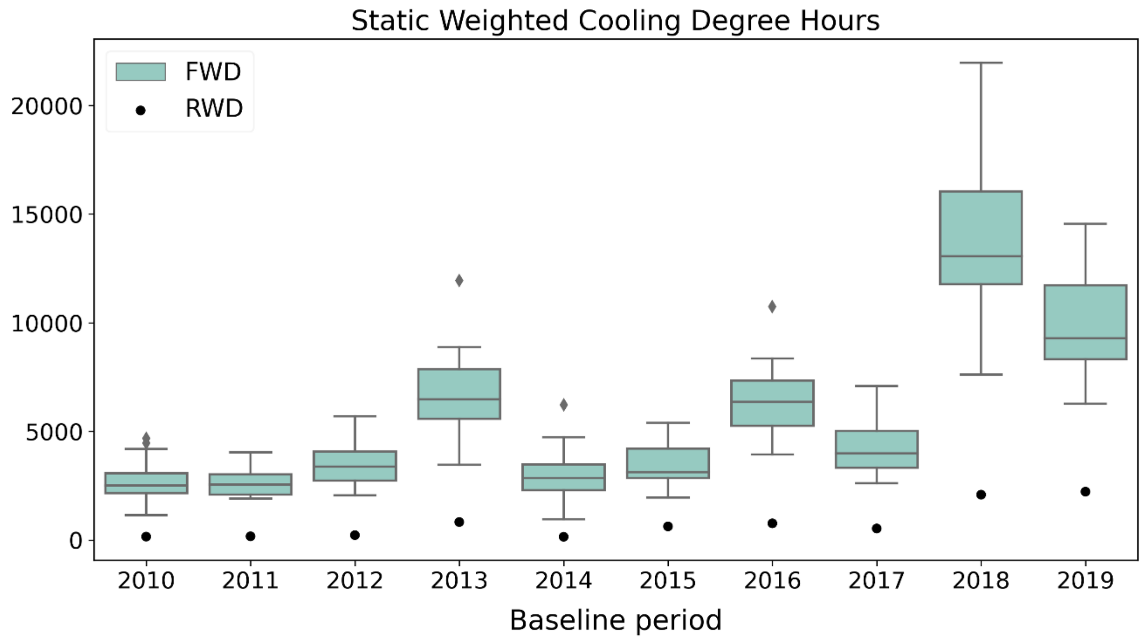
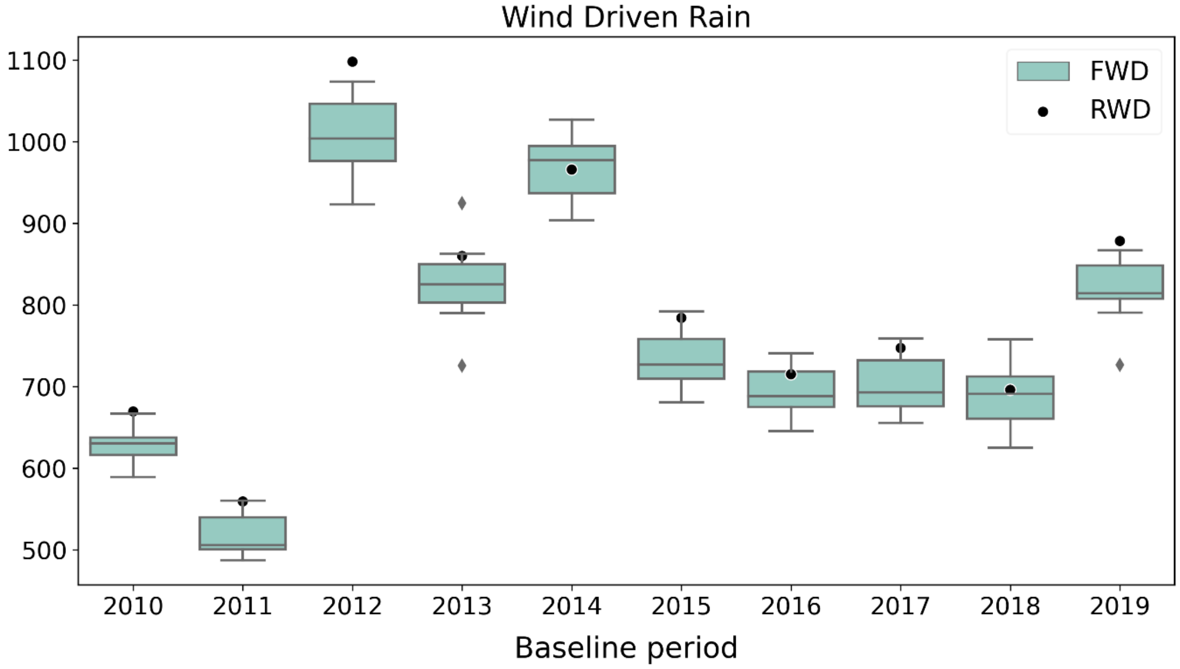


Figure D.8 WDR for the RWD and FWD (including the values of all the assessed future scenarios) for London.



HDD (Figure D.6) are considerably higher in the current weather file in relation to the morphed one (irrespective of the future scenario considered). The increase of outdoor temperature in the future period results in significantly higher values of SWCDH (Figure D.7) in the future period in contrast to the current one. Precipitation (Figure D.8) is generally higher in the current period although there is a considerable amount of uncertainty in the future period and for some future scenarios precipitation is greater in this period than in the current one. This uncertainty can be attributed to the fact that wind driven rain is computed from morphed rainfall and wind data; hence the combination of the two uncertain weather parameters is depicted in this figure.

Manchester

Figures D.9-D.11 display outdoor dry bulb temperature, global solar radiation and precipitation for both the RWD as well as its morphed file. For outdoor air temperature and global horizontal radiation future weather files produce higher values. As far as the precipitation is concerned, it can be observed that for some years (like 2016) the morphed file is more wet but for some others (like 2019) the opposite trend is noticed. Again, as observed for London for all the years within the baseline period (and looking into the values that correspond to the median future weather scenario) there are future scenarios that produce more precipitation than the current baseline period.

Figure D.9 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the RWD and FWD for Manchester.

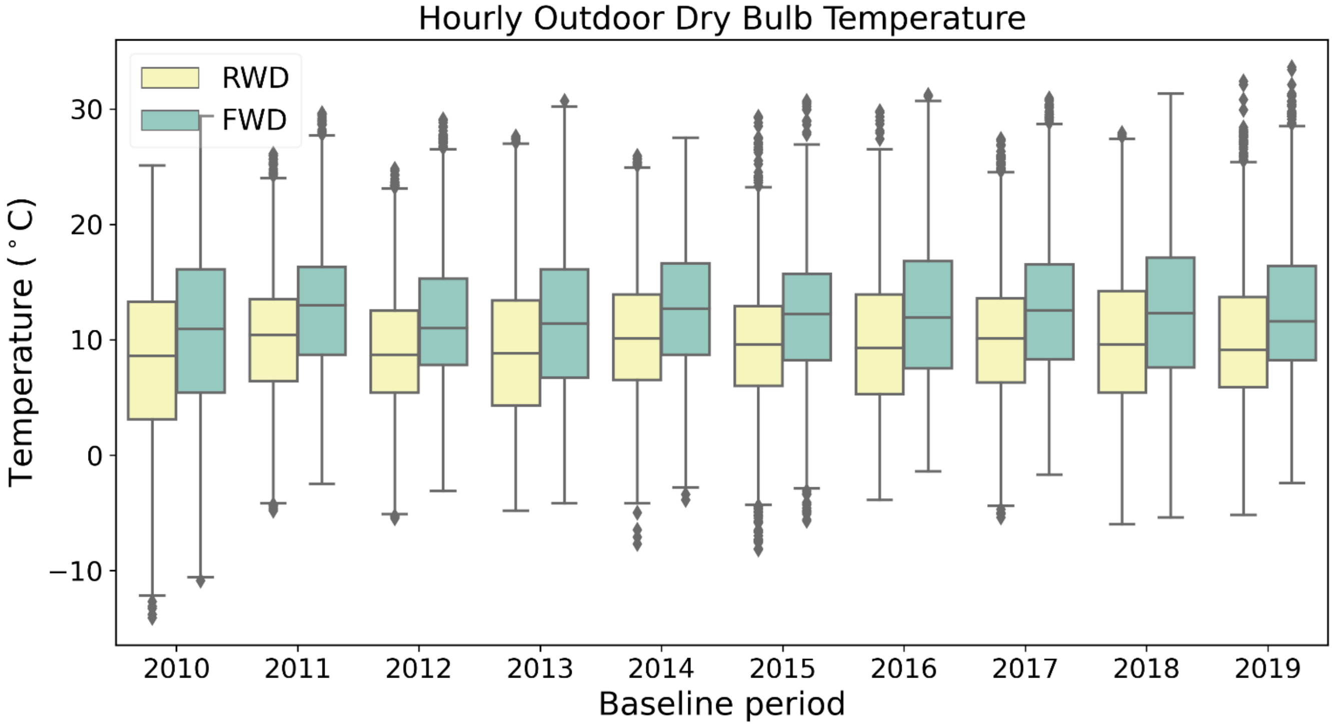


Figure D.10 Box-plot visualisation of the quartile distribution of the global radiation in the RWD and FWD for Manchester.

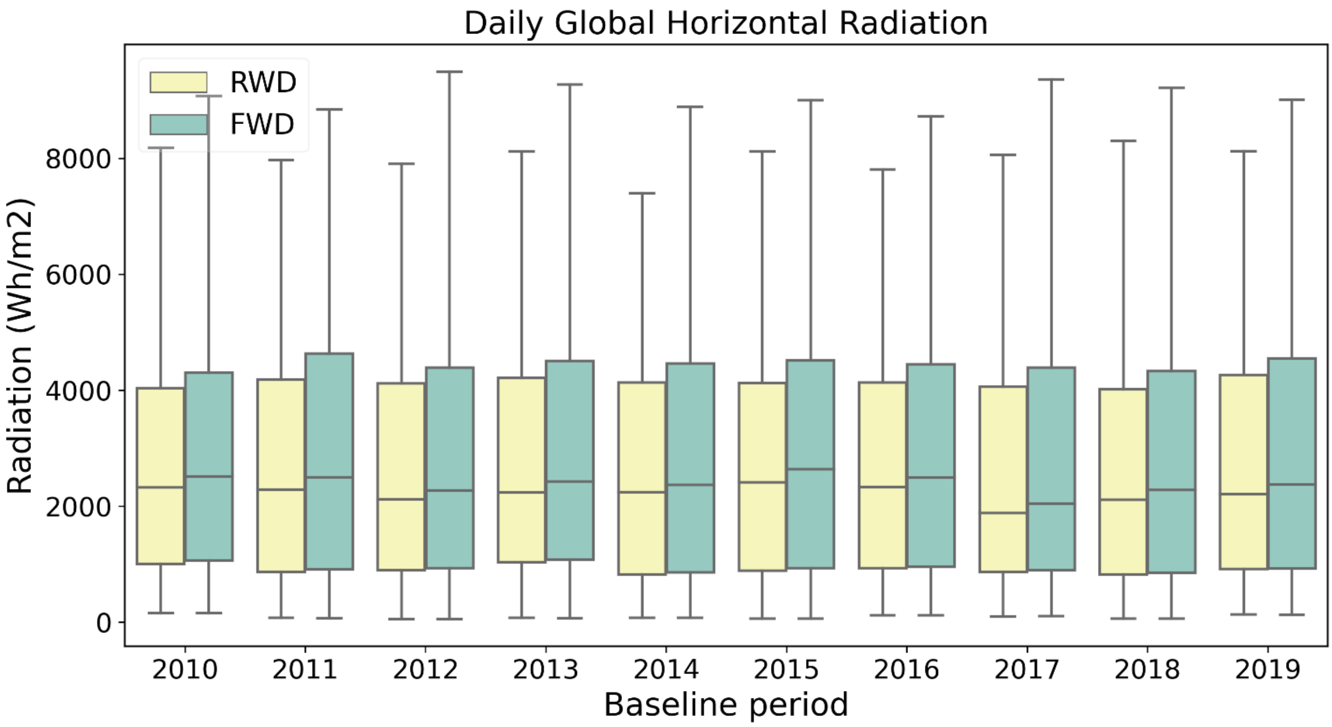
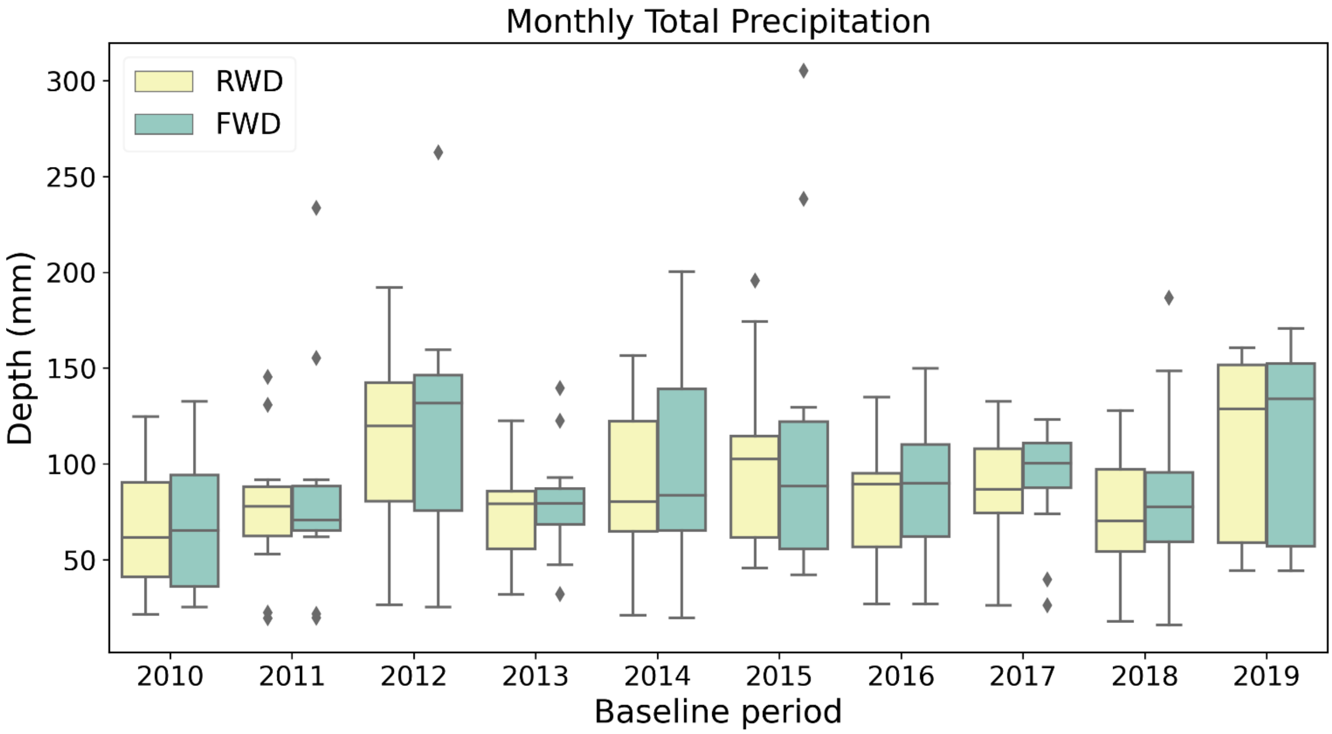


Figure D.11 Box-plot visualisation of the quartile distribution of the precipitation in the RWD and FWD for Manchester.



Figures D.12 and D.13 show daily outdoor temperature and hourly global radiation as well as direct normal and diffuse radiation In Figure D.12, as in the case of London, it can be seen that the main effect of morphing is the vertical shift of the temperature values of the original file.

Figure D.12 Daily outdoor temperature considering future weather scenario 5 for Manchester.

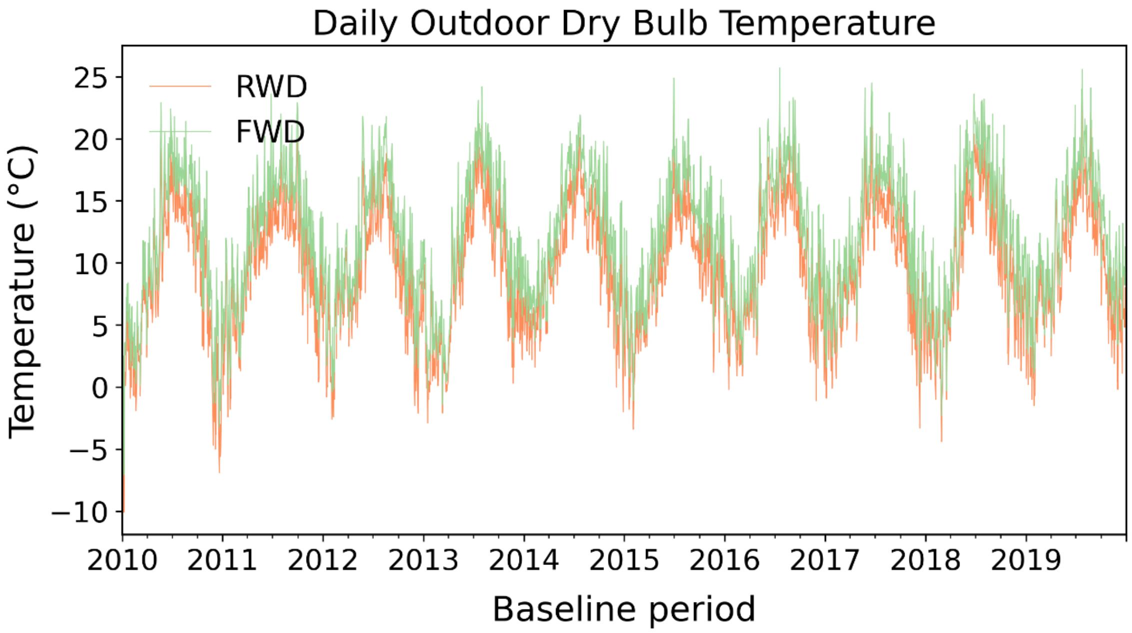
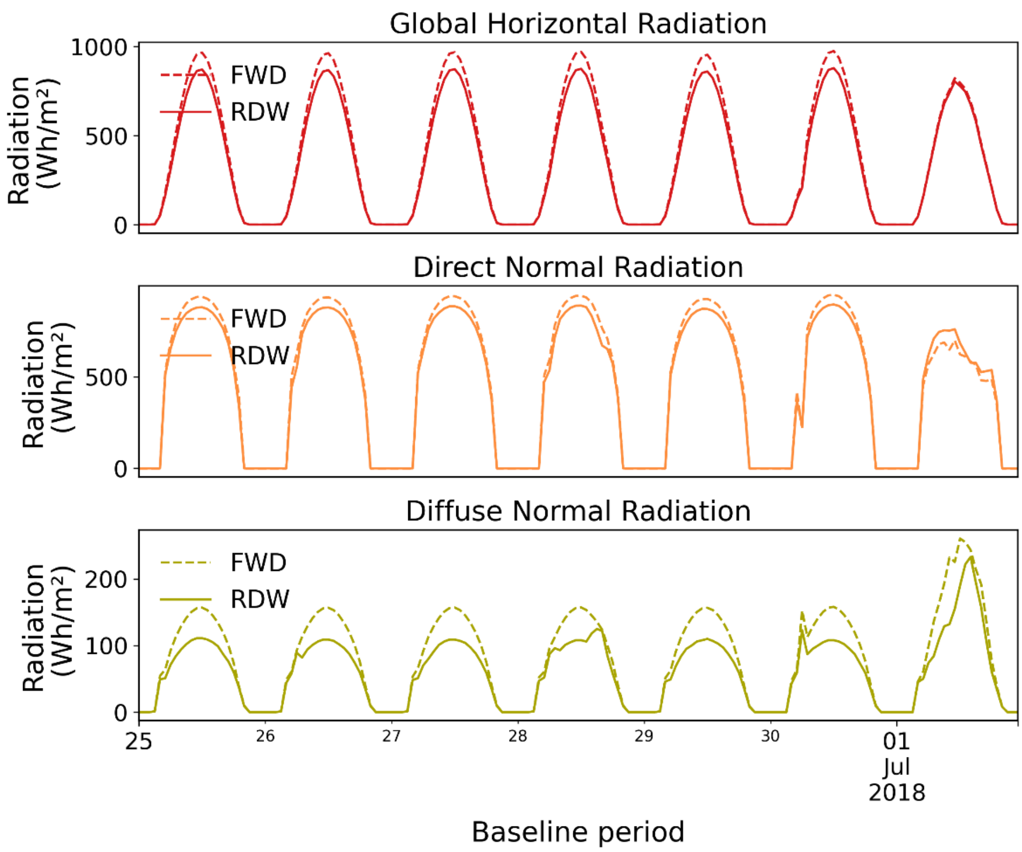


Figure D.13 Global, direct normal and diffuse solar radiation for future weather scenario 2 for Manchester.



Figures D.14-D.16 show a comparison between the RWD file and its morphed one considering the following metrics; HDD, SWCDH and WDR.

Figure D.14 HDD for the RWD and FWD (including the values of all the assessed future scenarios) for Manchester.

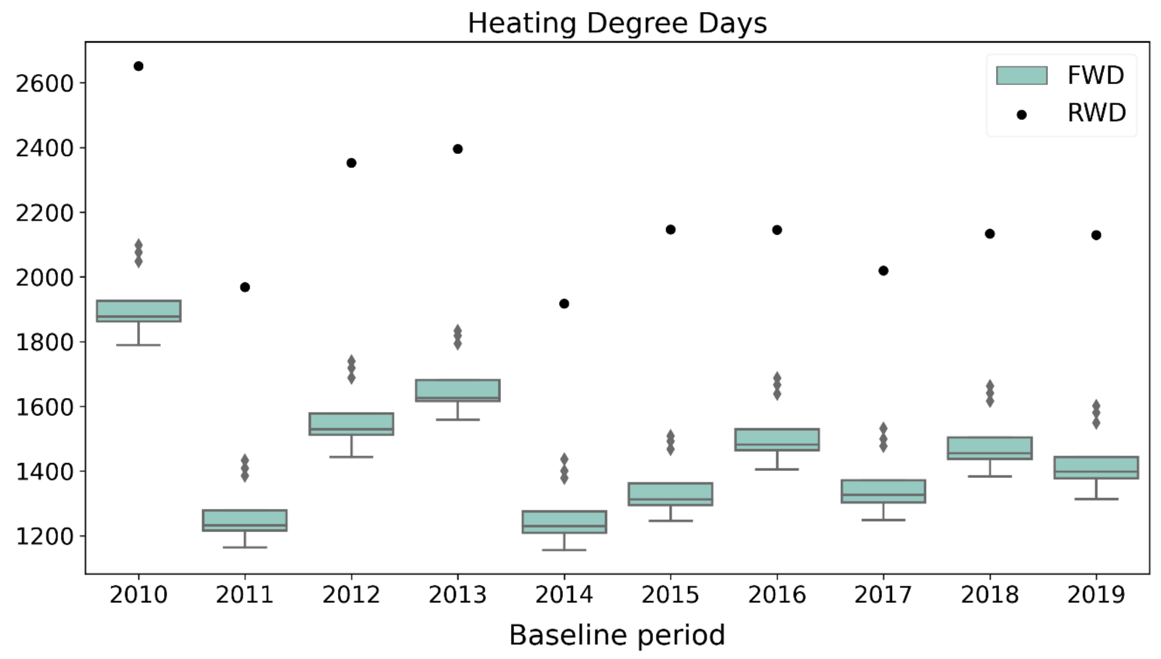


Figure D.15 SWCDH for the RWD and FWD (including the values of all the assessed future scenarios) for Manchester.

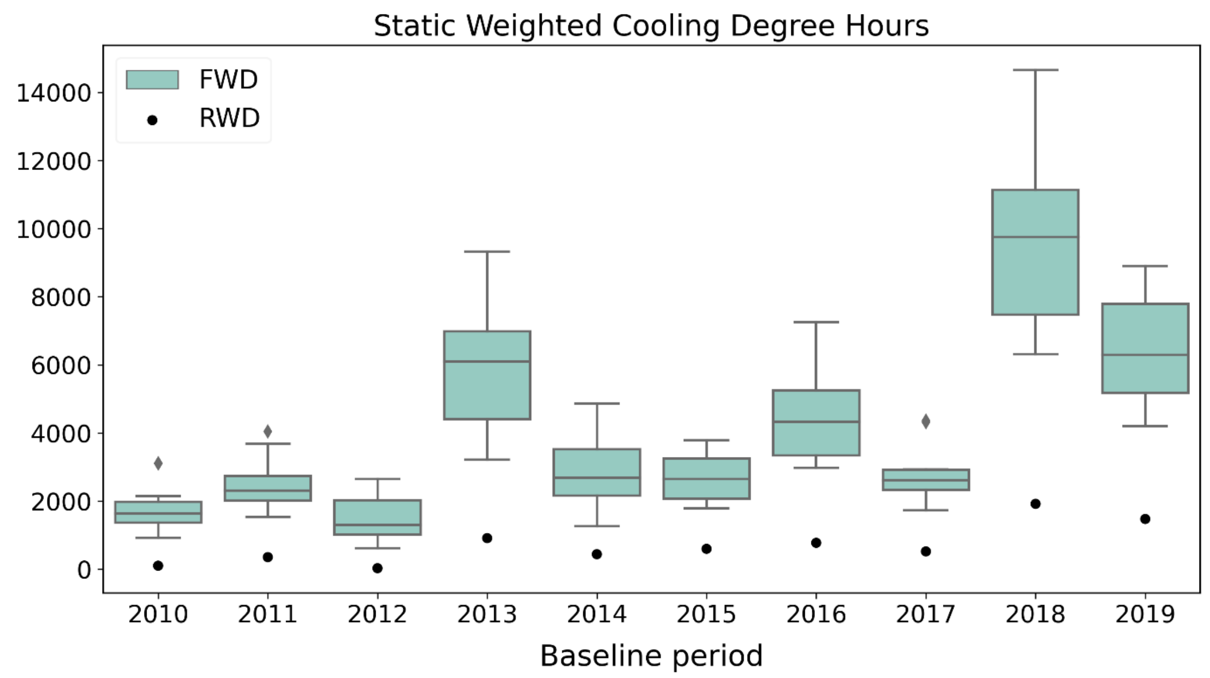
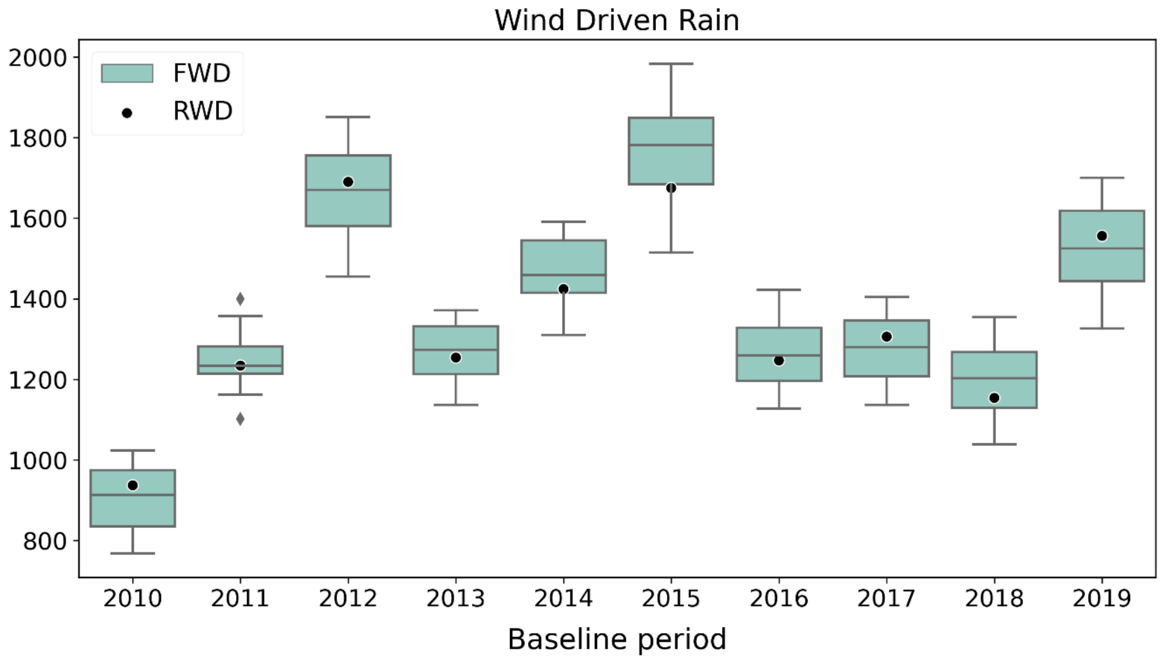


Figure D.16 WDR for the RWD and FWD (including the values of all the assessed future scenarios) for Manchester.



As in the case of London, HDD (Figure D.14) are considerably higher in the current weather file in relation to the morphed one (irrespective of the future scenario considered). The same pattern is observed for SWCDH (Figure D.15) as well. WDR (Figure D.16) in the FWD reflects the uncertainty present in the future weather scenarios.

Glasgow

Figures D.17-D.19 display outdoor dry bulb temperature, global solar radiation and precipitation for both the RWD as well as its morphed file. As in the other two locations, outdoor air temperature and global horizontal radiation are greater in the morphed weather files than in the current one. Precipitation (values that correspond to the median future weather scenario) is in general higher in the morphed file with the exception of 2016 where the opposite trend is observed. As it was noticed for London and Manchester, precipitation values in some future scenarios exceed those values in the current baseline period although the phenomenon is not so intense as in the other two locations.

Figure D.17 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the RWD and FWD for Glasgow.

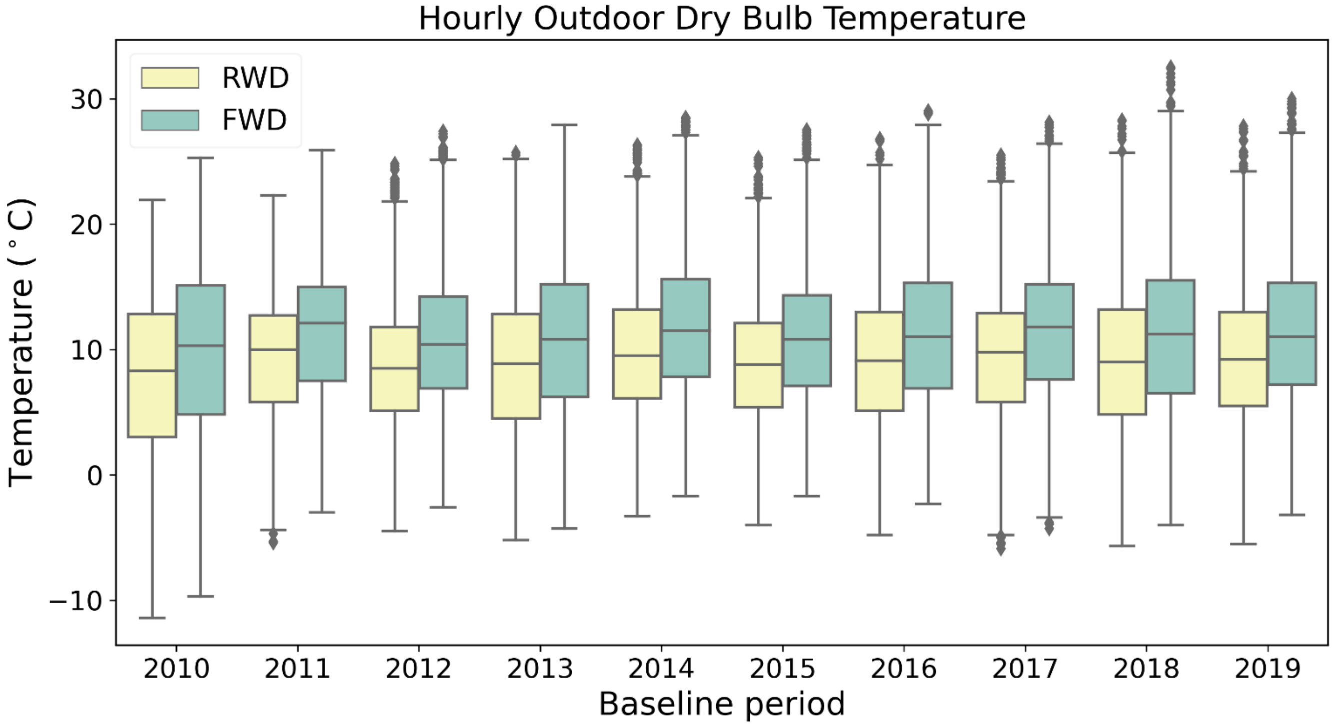


Figure D.18 Box-plot visualisation of the quartile distribution of solar radiation in the RWD and FWD for Glasgow.

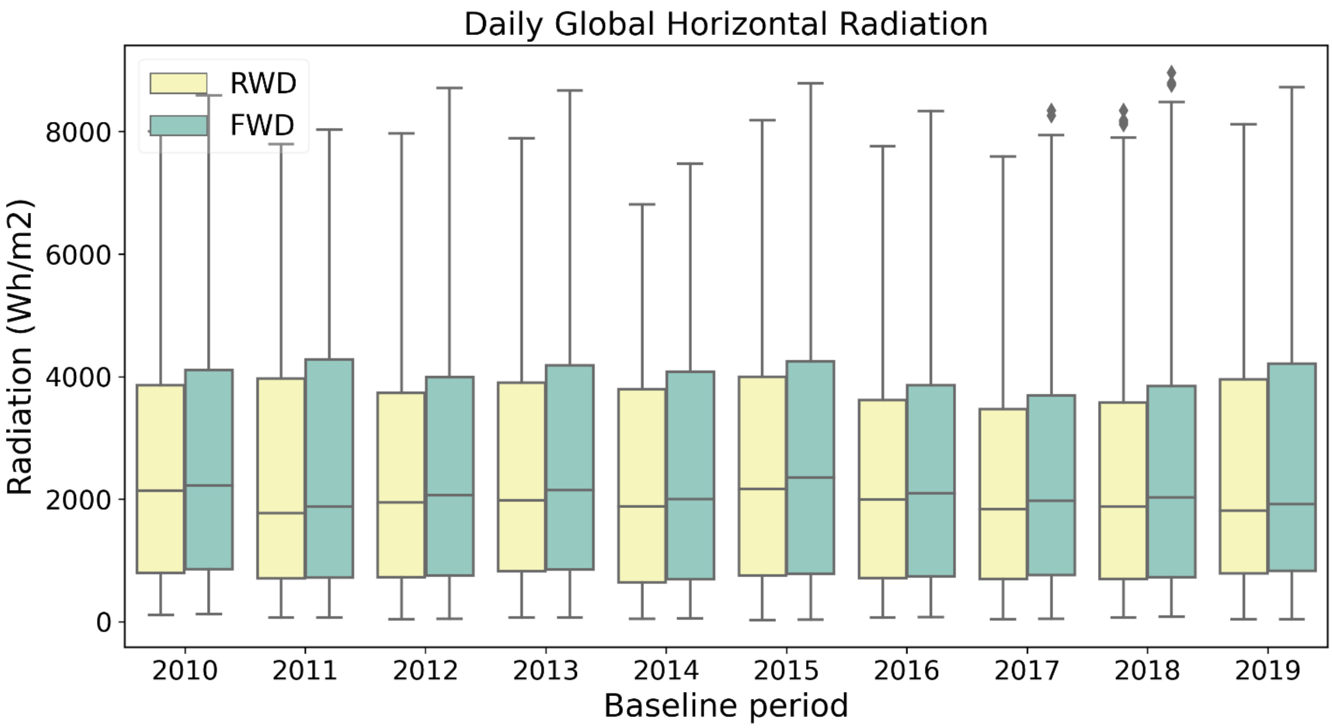
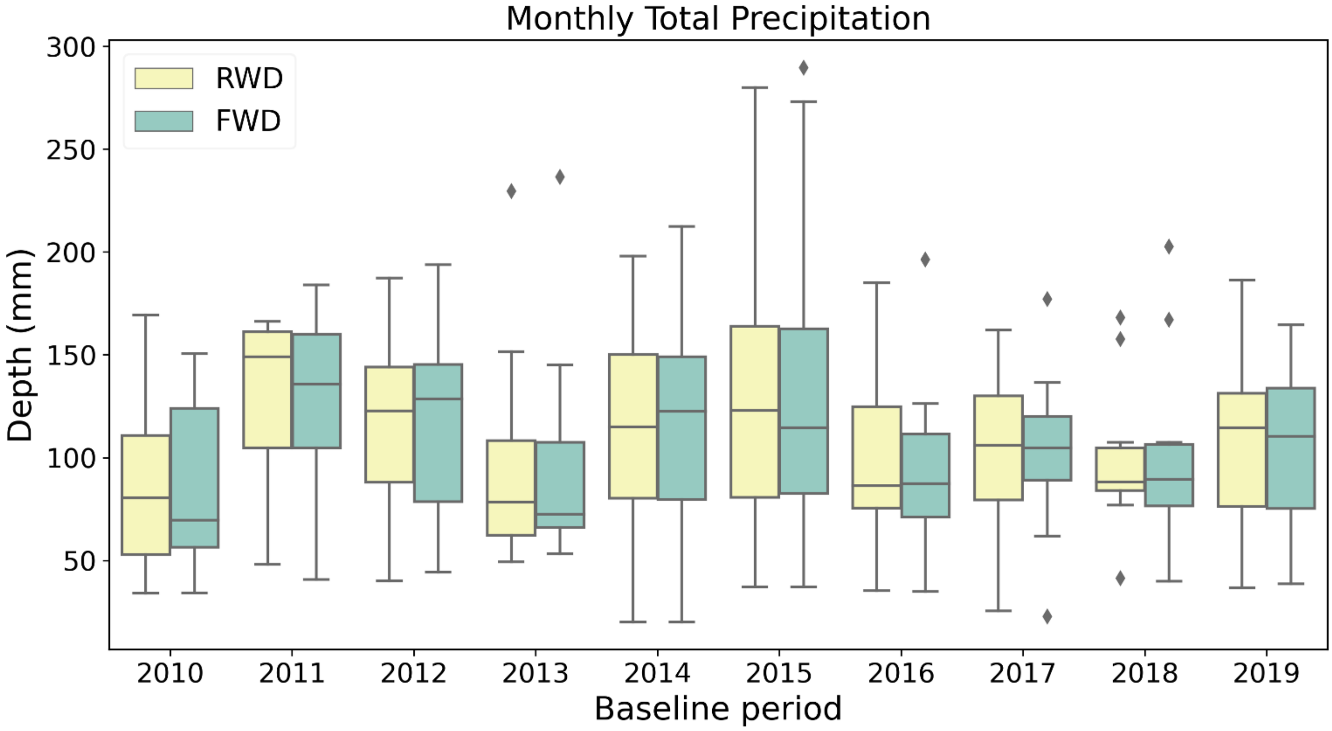


Figure D.19 Box-plot visualisation of the quartile distribution of precipitation in the RWD and FWD for Glasgow.



Figures D.20 and D.21 show daily outdoor temperature (for future weather scenario 5) and hourly global radiation as well as direct normal and diffuse radiation (for future weather scenario 2). In Figure D.20, it can be seen that the main effect of morphing is the vertical shift of the temperature values of the original file which is not as intense as it is in the other two locations (and especially in the case of London.)

Figure D.20 Daily outdoor temperature considering future weather scenario 5 for Glasgow.

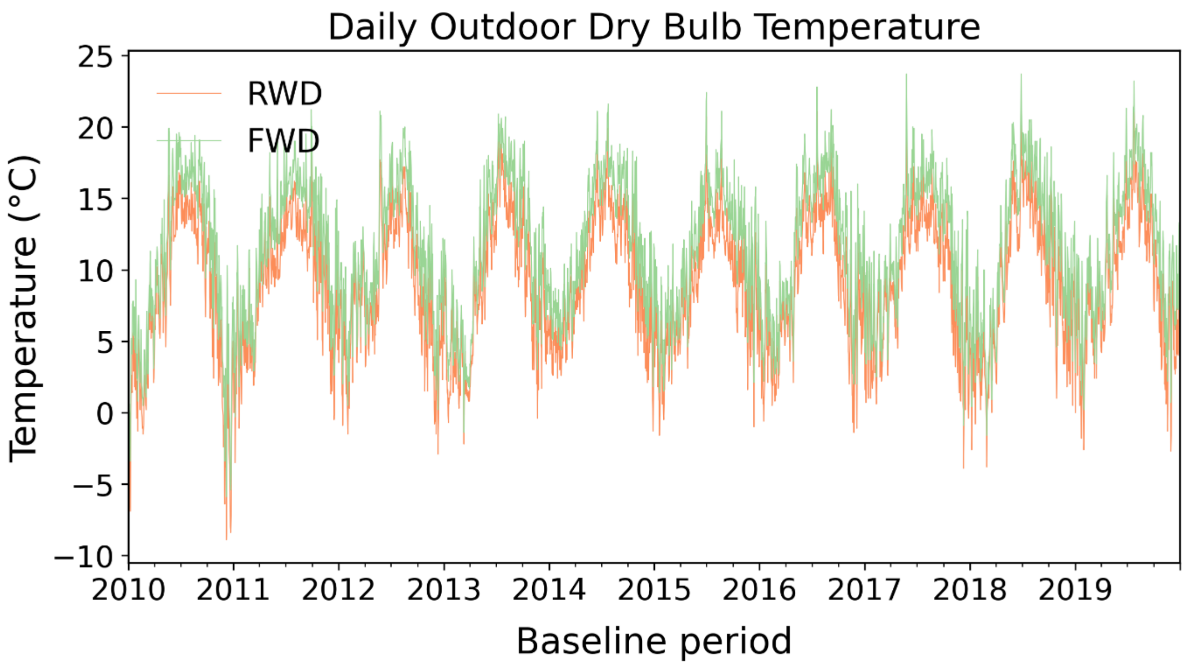
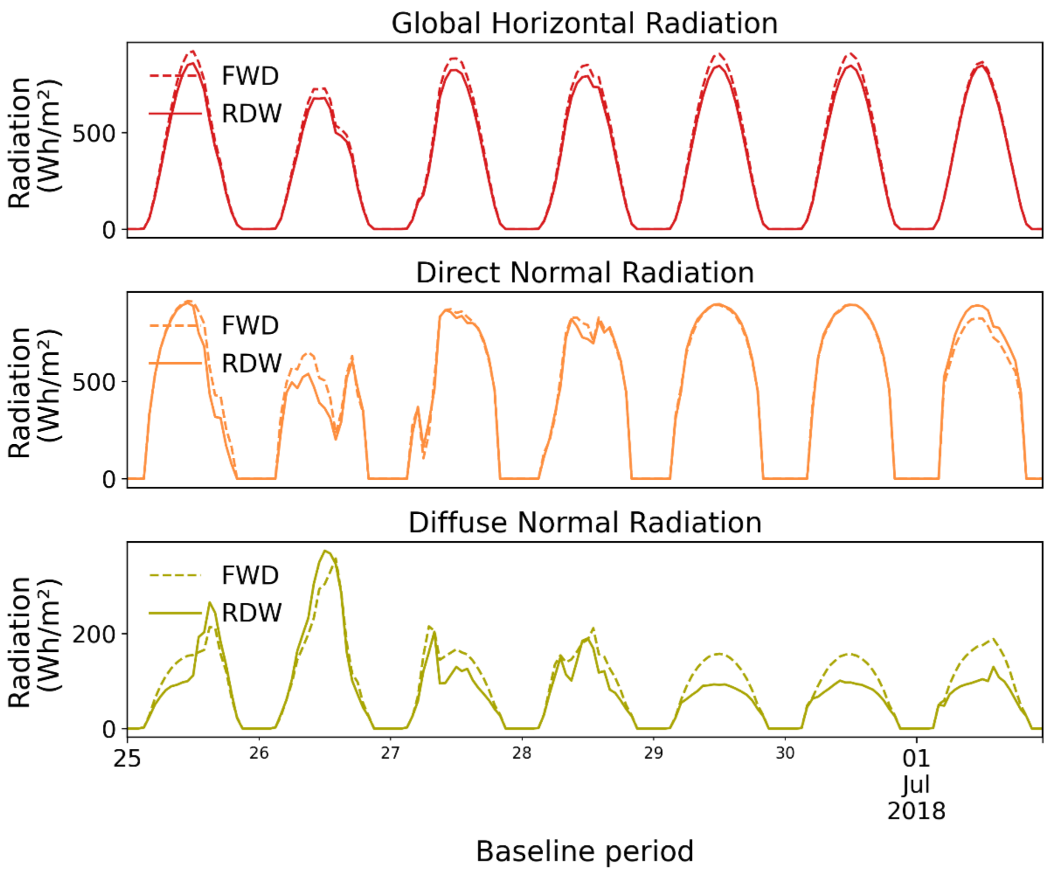


Figure D.21 Global, direct normal and diffuse solar radiation for future weather scenario 2 for Glasgow.



Figures D.22-D.24 show a comparison between the RWD file and its morphed one considering the following metrics; HDD, SWCDH and WDR.

Figure D.22 HDD for the RWD and FWD (including the values of all the assessed future scenarios) for Glasgow.

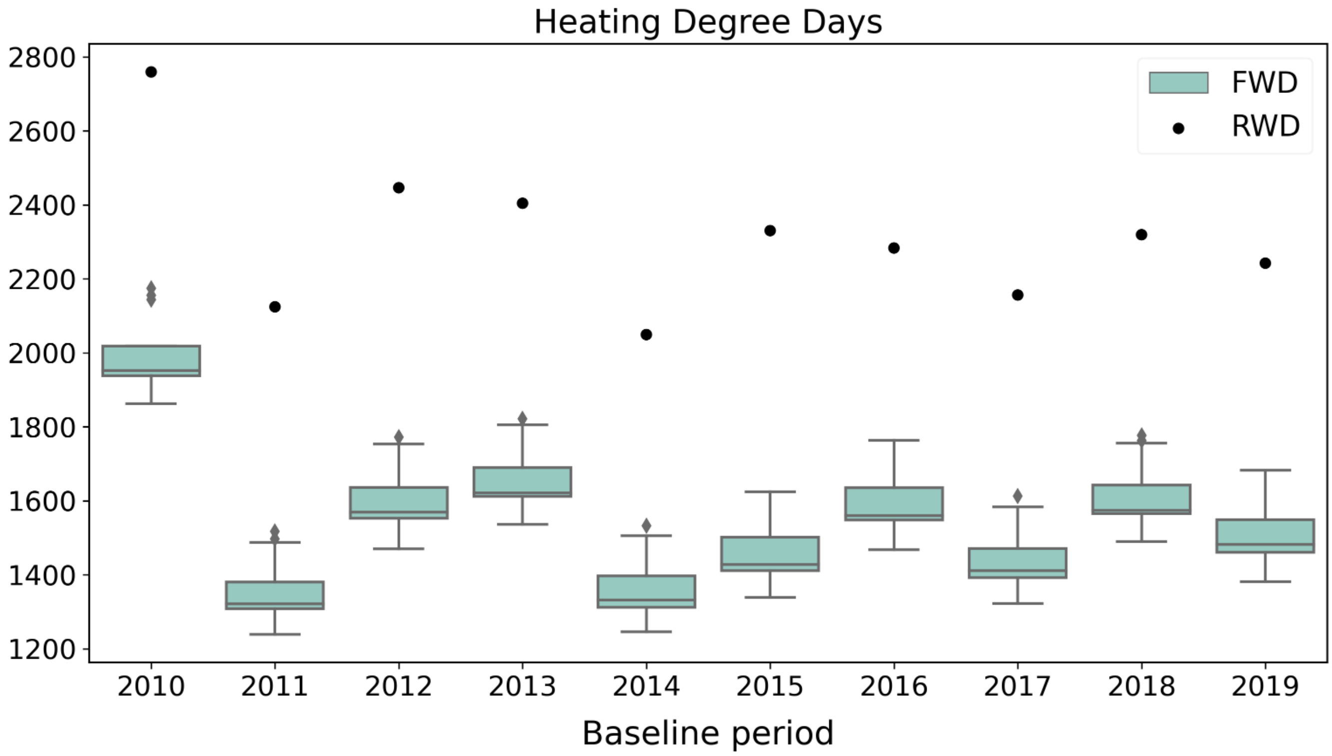


Figure D.23 SWCDH for the RWD and FWD (including the values of all the assessed future scenarios) for Glasgow.

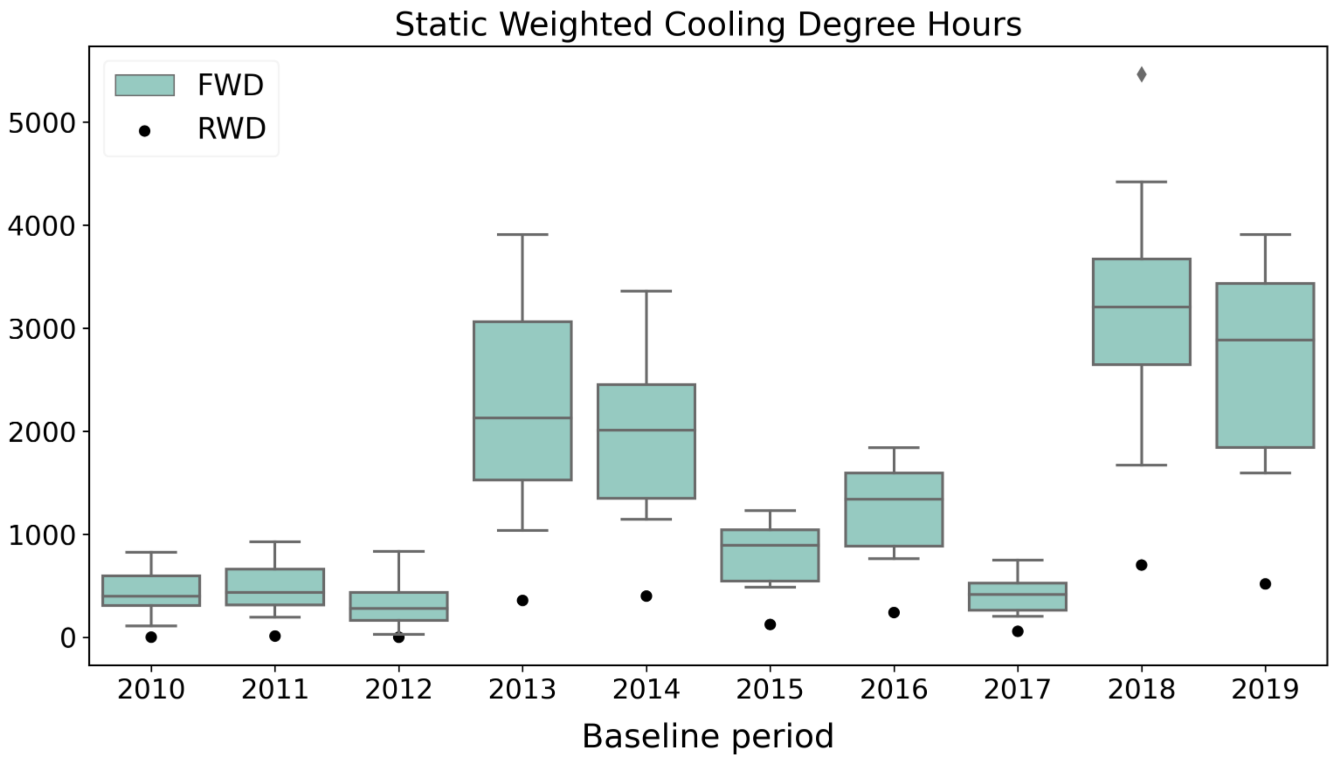
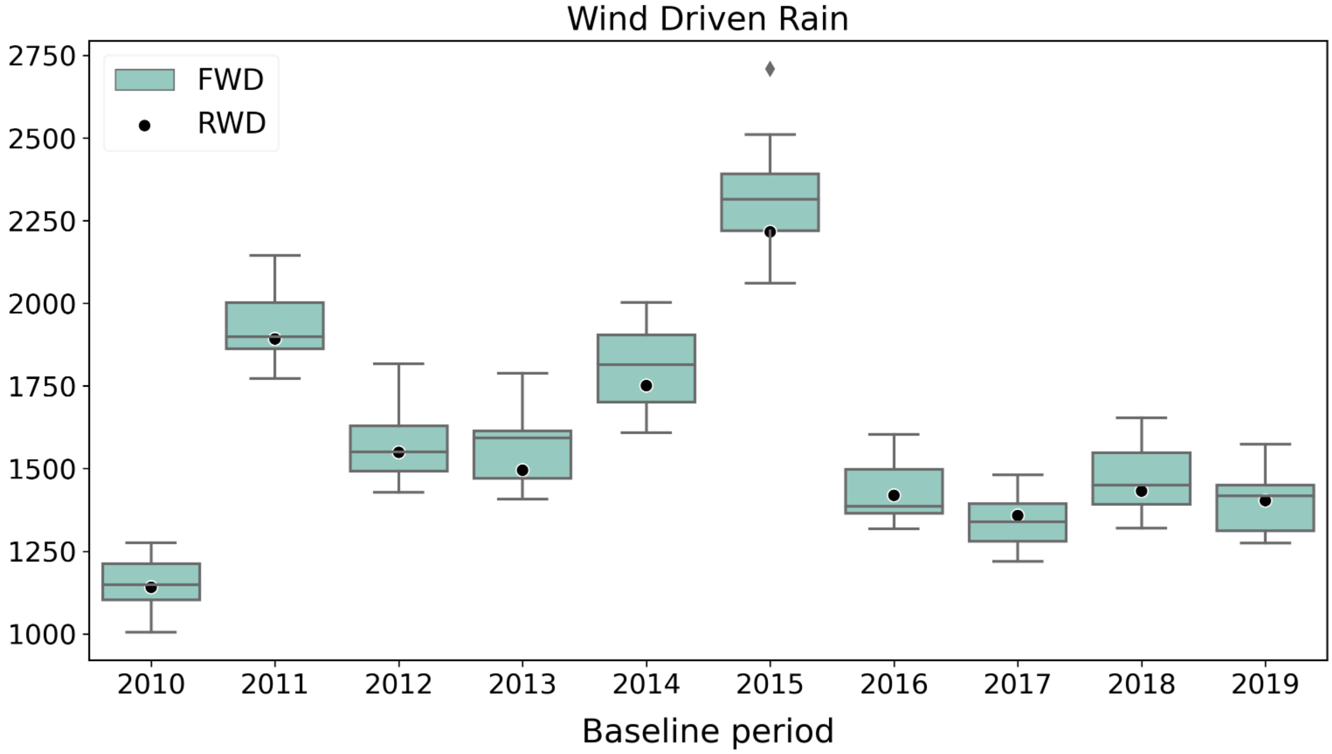


Figure D.24 WDR for the RWD and FWD (including the values of all the assessed future scenarios) for Glasgow.



As it was noticed for London and Manchester, HDD (Figure D.22) are much higher in the current weather file in relation to the morphed one (irrespective of the future scenario considered). The same motive is observed for SWCDH (Figure D.23) as well. WDR (Figure D.24) in the FWD reflects the uncertainty present in the future weather scenarios.

Appendix E: Weather data from FWD

This section displays monthly daily maximum outdoor temperature, monthly radiation and monthly precipitation for the twelve future scenarios considered in the construction of the FWD files. The above data are shown for London, Manchester, and Glasgow. These graphs depict the amount of uncertainty in the twelve different future weather scenarios considered in this work.

London

Figure E.1 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the FWD for London.

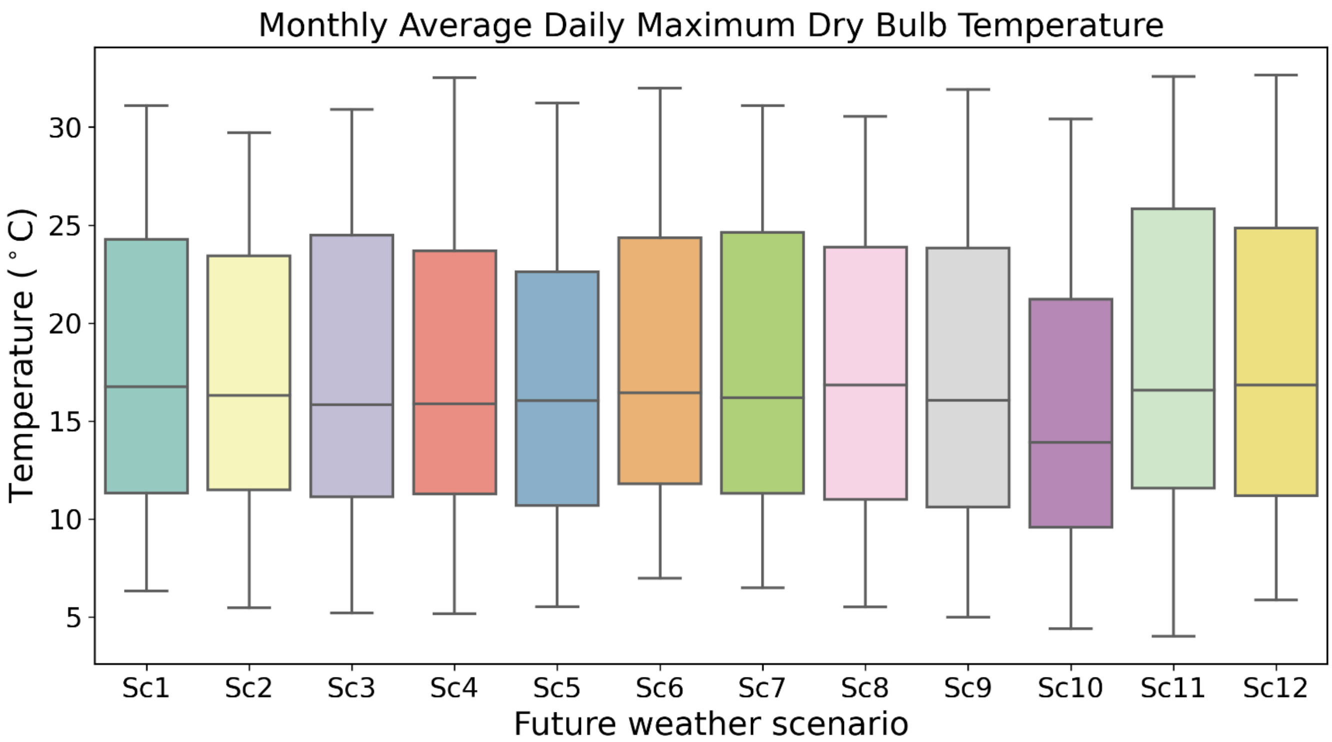


Figure E.2 Box-plot visualisation of the quartile distribution of global radiation in the FWD for London.

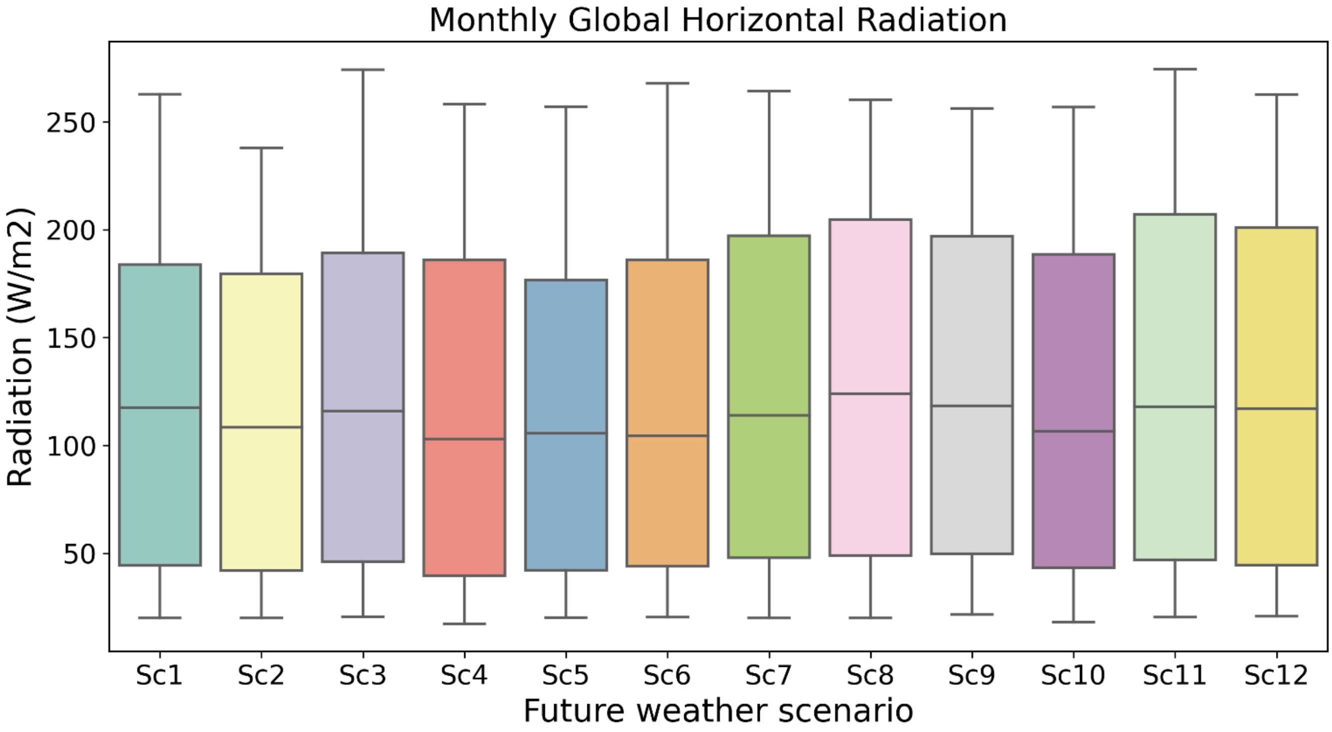
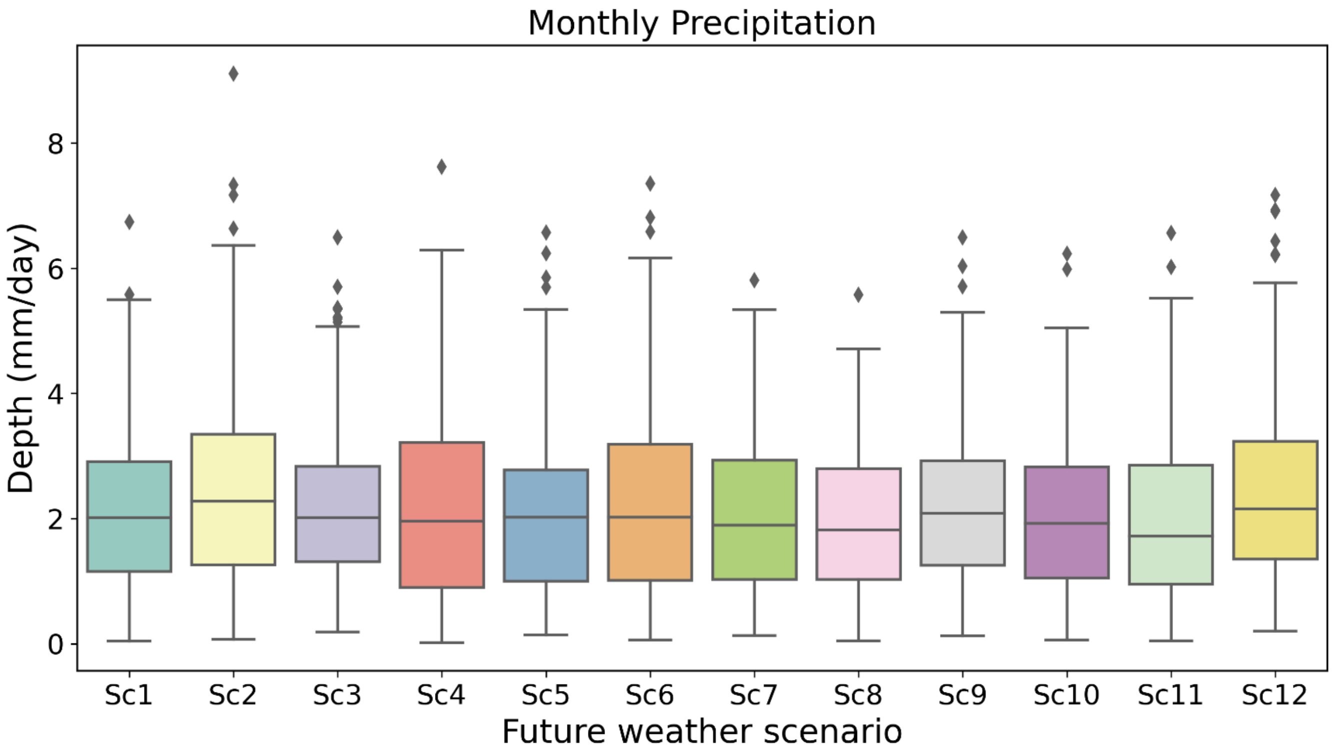


Figure E.3 Box-plot visualisation of the quartile distribution of the precipitation in the FWD for London.



Manchester

Figure E.4 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the FWD for Manchester.

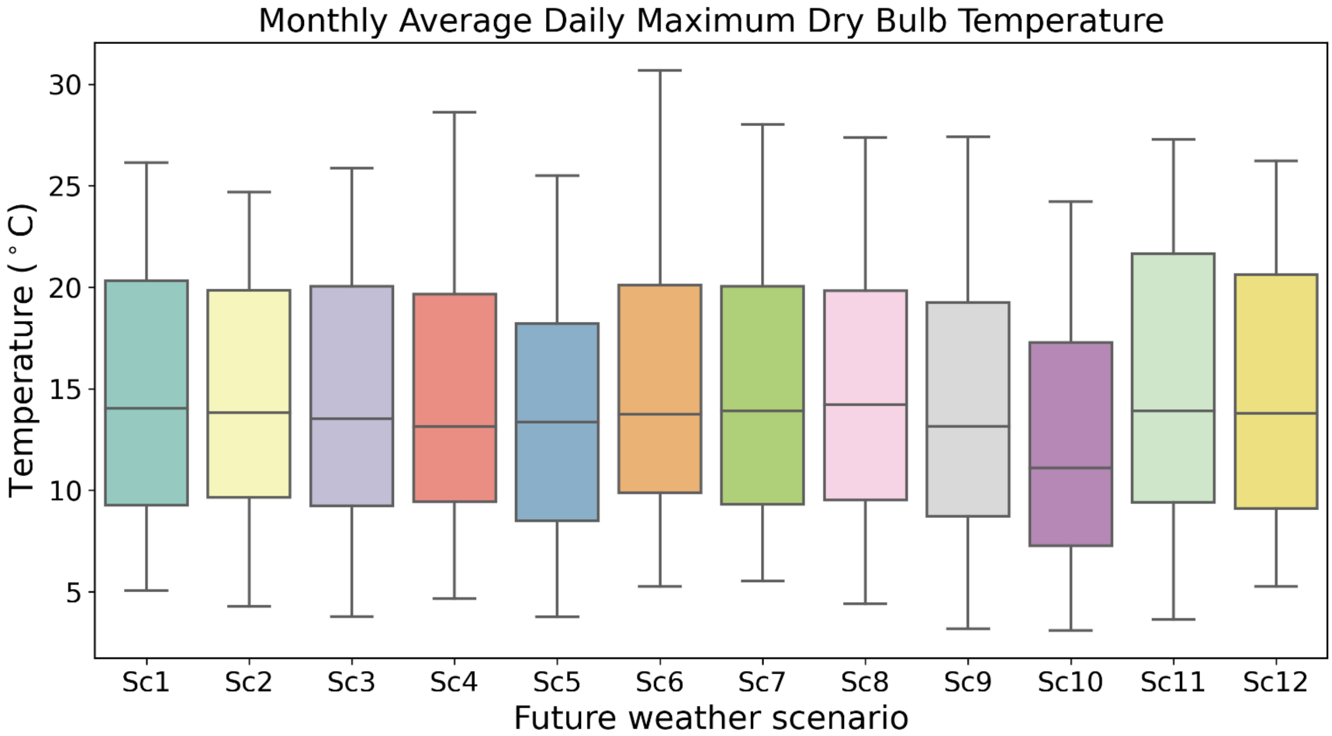


Figure E.5 Box-plot visualisation of the quartile distribution of global radiation in the FWD for Manchester.

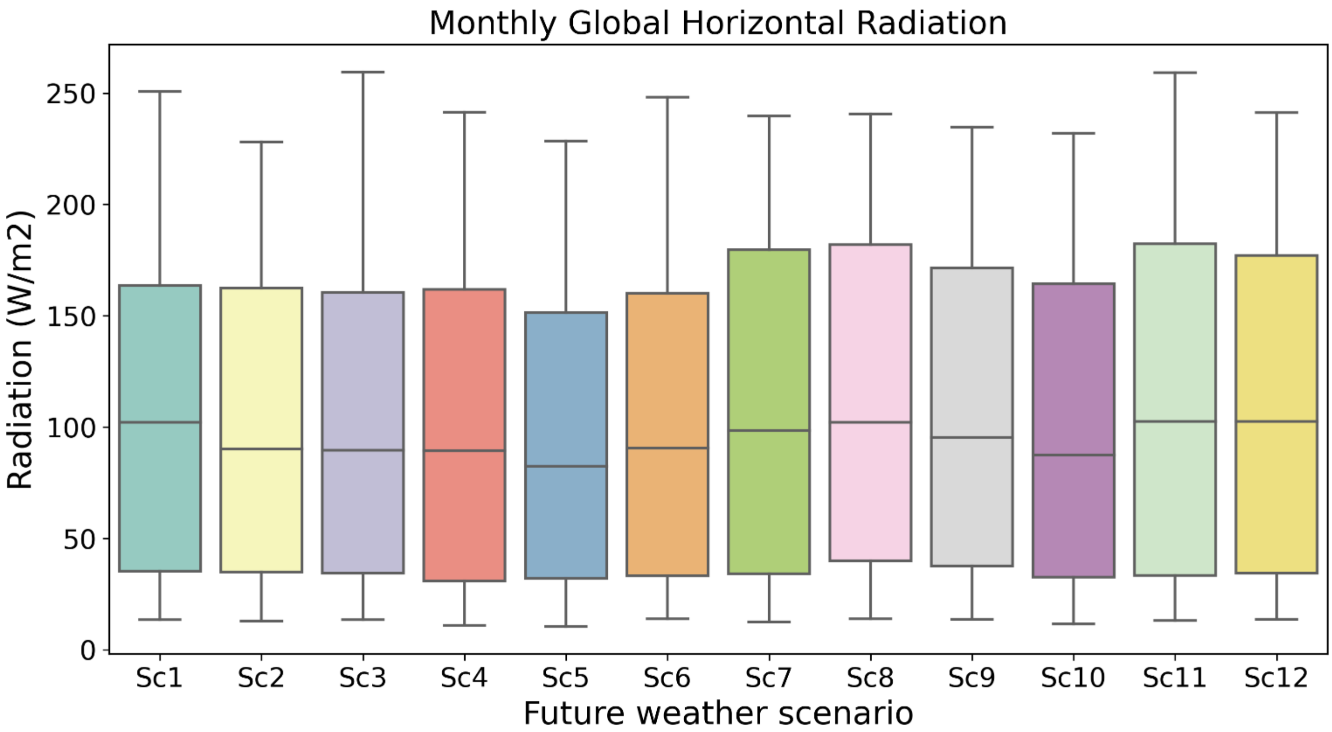
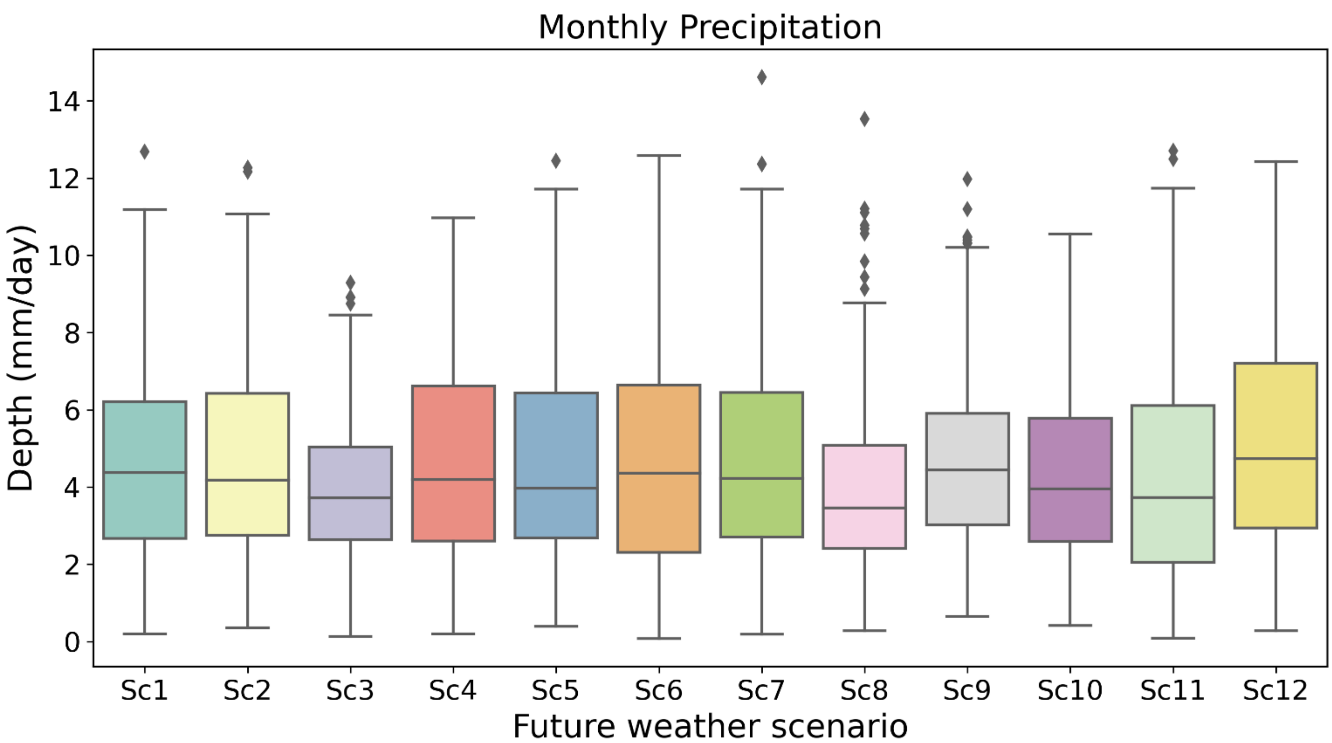


Figure E.6 Box-plot visualisation of the quartile distribution of the precipitation in the FWD for Manchester.



Glasgow

Figure E.7 Box-plot visualisation of the quartile distribution of the outdoor dry bulb temperature in the FWD for Glasgow.

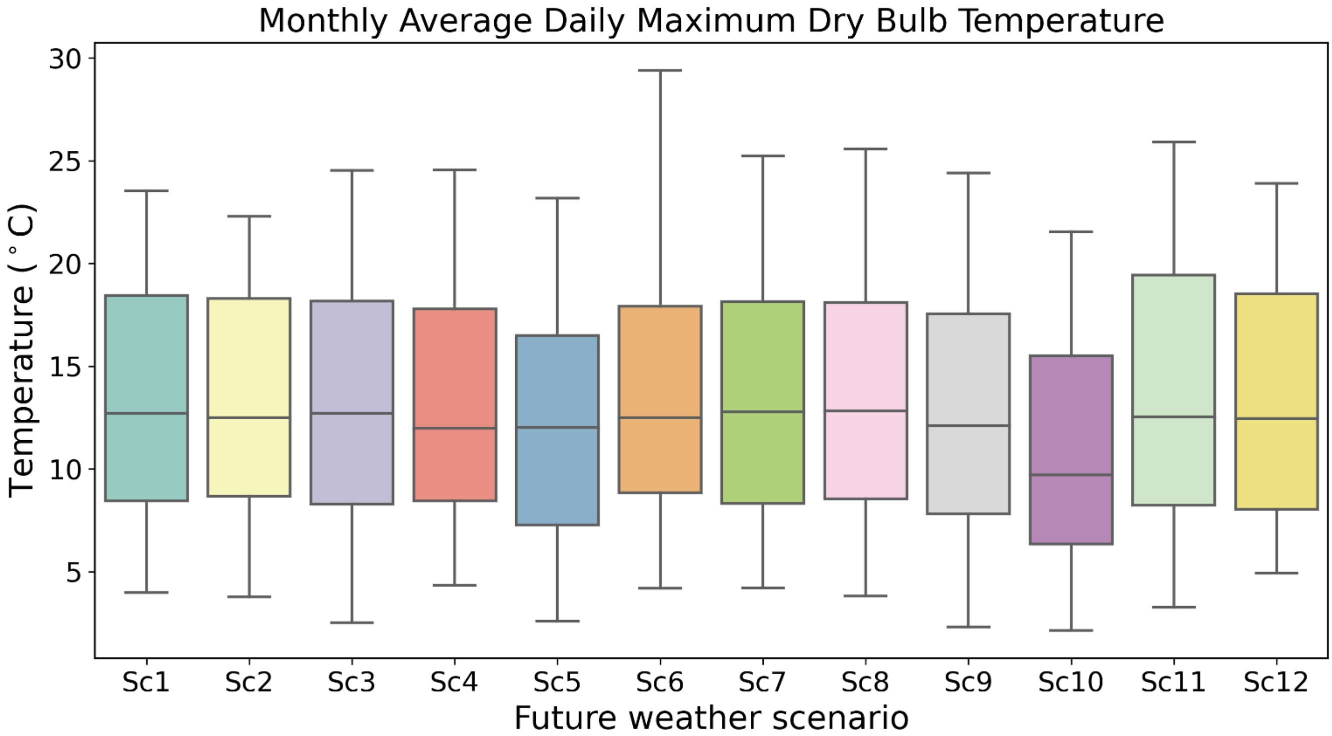


Figure E.8 Box-plot visualisation of the quartile distribution of global radiation in the FWD for Glasgow.

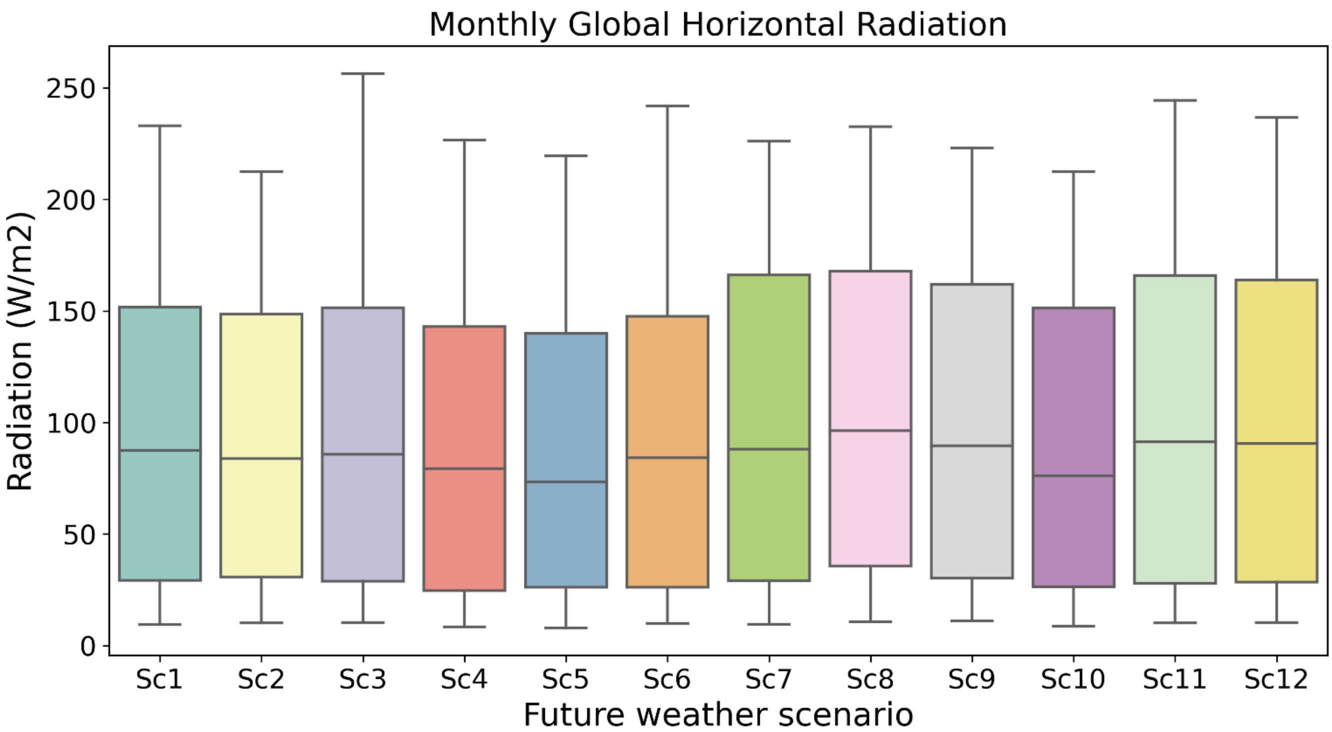
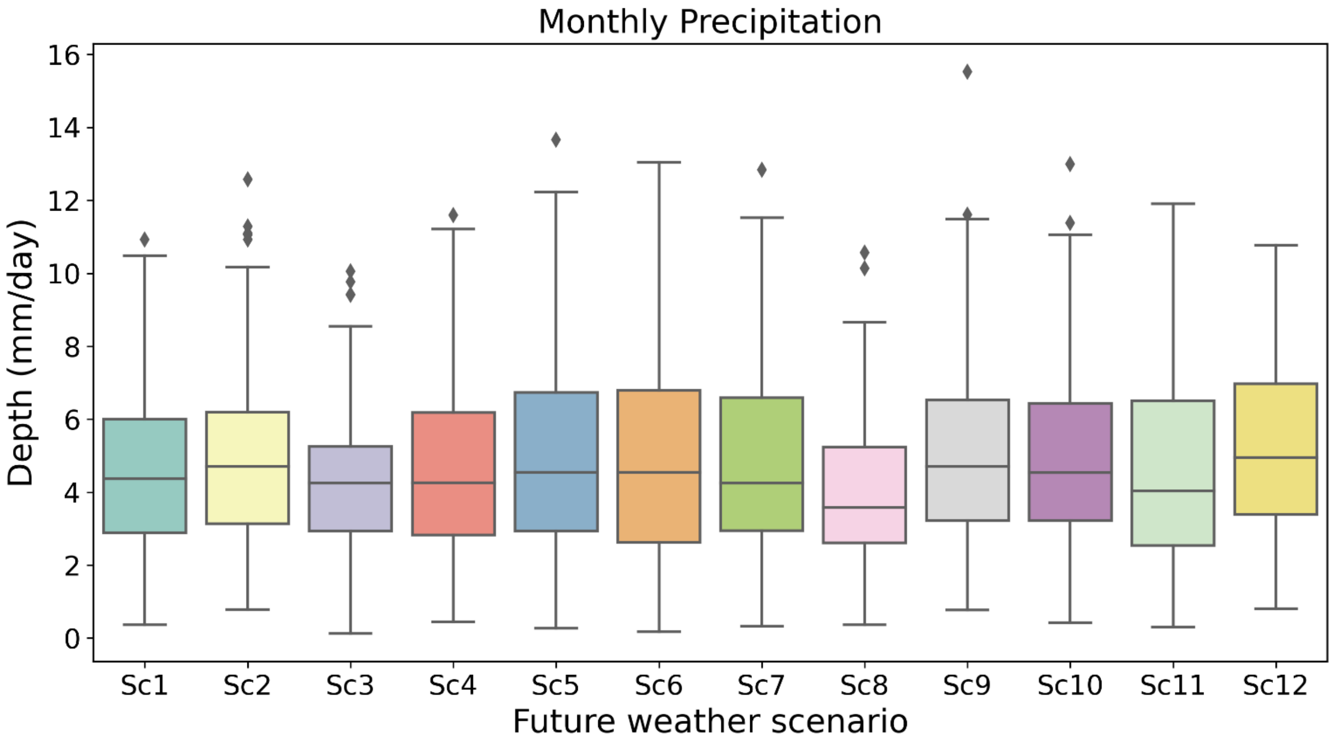


Figure E.9 Box-plot visualisation of the quartile distribution of the precipitation in the FWD for Glasgow.



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