Creation Of Future Hot Event Years For Assessing Building Resilience Against Future Deadly Heatwaves

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Abstract

Building resilience to warming climate has been assessed via dynamic thermal simulation with future summer reference years, i.e. warmer than typical year. However, previous efforts on the creation of future summer reference years did not take account of heatwaves which was projected to be more frequent and intense in the future due to climate change. Different heatwave definitions were evaluated in terms of their impacts on the risk of heat-related deaths in non-air conditioned buildings. This study found out a heatwave criterion suitable for the creation of future Hot Event Years (HEYs) for use in building resilience assessment against deadly heatwaves. Building practitioners will find future HEYs useful in providing building adaptations to ensure safe indoor environment against changing climate.

Introduction

Building resilience to heatwave has become a crucial problem. The 2003 European heatwave which was recorded as the hottest event in the past 500 years caused 52,000 fatalities (Larsen, 2006). Among the various risk factors such as health conditions, housing conditions, social status, environmental conditions (e.g. urban heat island) and behavioural factors, poor building designs (e.g. lack of insulation) were regarded as the principle risk factors for such a devastating heatwave (Vandentorren *et al.*, 2006). The Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013) reported that frequency, intensity and duration of heatwaves are likely to increase in the future. Thus, there is a great concern that buildings, especially non-air-conditioned buildings such as UK dwellings, would fail to protect occupants from future heatwaves if without any building adaptations. As evidence of this, the risk of heat-related mortality would be tripled by the 2050s (Liu *et al.*, 2017; ASC, 2016).

Nowadays, building simulations with future summer reference years have become a common technique to assess overheating risk and building resilience against warming climate. Nevertheless, previous efforts on the creations of future summer reference years (CIBSE, 2016; Eames *et al.*, 2011; Liu *et al.*, 2016; Watkins *et al.*, 2012) have not taken account of heatwaves. So, none of existing future weather files are suitable for a critical evaluation of the risk of internal heat-related deaths under future heatwaves. Historical climate data containing heatwaves could be used to evaluate building resilience. However, as

stated before, future heatwaves are very likely to become more severe due to climate change (IPCC, 2013). Hence, thermal performance of buildings should be assessed against future heatwaves rather than historical heatwaves since more severe heatwaves result in a higher risk of heat-related deaths especially in buildings that rely on natural ventilation during summer.

Hence, future climate data is necessary to produce extreme years that contain future heatwaves. The UKCP09 Weather Generator (UKCP09 WG) developed by Jones *et al.* (2010) can output future climate data which have been used to produce future weather files for building simulations (Eames *et al.*, 2011; Liu *et al.*, 2016; Du *et al.*, 2011; Smith and Hanby, 2012). Each run of the UKCP09 WG produces 100 sets of 30-year long synthetic weather data, i.e. 3000 sample years by given location. Both hourly and daily data are produced for control year (1960 to 1990) and future year (e.g. 2020s and 2080s) at the same time under a chosen emission scenario (low, medium or high). Future weather data is available for seven decadal time slices from the 2020s to the 2080s. The low, medium and high emission scenarios used in UKCP09 WG correspond to SRES B1, SRES A1B and SRES A1FI respectively which can be found in the IPCC Special Report on Emission Scenarios (SRES). The UKCP09 WG has been updated by improving its capabilities in generating extreme weather events. The updated version was referred to as Spatial Urban Weather Generator (Spatial WG) (Kilsby *et al.*, 2011). Therefore, future heatwaves could be extracted from synthetic future weather data sets produced by the Spatial WG based on heatwave definitions. An appropriate heatwave criterion should be adopted to identify catastrophic heatwaves in the synthetic future weather data set produced by the Spatial WG.

The basic definition of heatwave could be temporary hot spells (last at least two consecutive days) that cause adverse influence on human health (Robinson, 2001). However, there are no universal heatwave criteria as it could vary across different climatic regions and for different usages. According to a systematic review on different heatwave criteria by Xu *et al.* (2016), all of previous studies have defined a heatwave based on either relative or absolute temperature thresholds. In general, Xu *et al.* (2016) found that mean temperatures were used as relative thresholds, e.g. mean temperatures exceed 97th percentile for at least two consecutive days (Gasparrini and Armstrong, 2011) while maximum temperatures were

used as absolute thresholds, e.g. maximum temperatures exceed 35 °C for at least two consecutive days (Tong *et al.*, 2010). In addition, the daytime and overnight maximum temperature thresholds, e.g. 30 °C and 15 °C set by Heat-Health Watch Service in England while 26.6 °C (80 °F) and 40.6 °C (105 °F) by the National Weather Service in the United States, were adopted as heatwave criteria. Instead of using a single weather variable, the combination of temperature and humidity were used to define a heatwave as these weather variables could be regarded as primary factors to the human thermal physiology (Robinson, 2001; Mora *et al.*, 2017). Mora *et al.* (2017) have used Support Vector Machines (SVMs) to separate the global hot events into lethal and non-lethal hot events. If the climatic conditions were above the 95% probability of the temperature-humidity SVM, it was regarded as deadly heatwaves. This global SVM decision boundary, i.e. heatwave criterion was used to analyse the risk of heat-related mortality over the world under different future climate scenarios.

These heatwaves basically were defined in terms of outdoor climatic conditions. In addition, heatwaves could be classified into deadly and non-deadly hot events (Mora *et al.*, 2017), indicating that different heatwaves might have significantly different impacts on indoor thermal comfort. It is therefore unknown whether any of the existing heatwave criteria is suitable for identifying future heatwaves in the future synthetic weather data set. This study aimed to find out an appropriate heatwave criterion for the creation of future hot event years (HEYs) for use in building resilience assessment against future deadly heatwaves.

Methods

Heatwave definitions

Three heatwave definitions from World Meteorological Organisation (WMO), UKCP09 and UK Met Office National Severe Weather Warning Service (NSWWS) are shown in Table 4. These existing heatwave definitions also have been used in previous study (Patidar *et al.*, 2013) on the impact of heatwave on overheating and passive adaptations. Heatwave-1 and Heatwave-2 are relative heatwave thresholds while Heatwave-3 is an absolute heatwave threshold used by the UK Health Watch system (see Table 4). The temperature thresholds for heatwave-1 and heatwave-2 suggested by Patidar *et al.* (2013) were 24.6 °C and 18.6 °C respectively which were adopted in this study.

Creation of future HEYs

Figure 1 shows creation of future HEYs from 3000 sample years generated by Spatial WG. First, future weather data were generated for city of London (51.49 °N, 0.45 °W), UK for the 2020s and 2080s under median emission scenario by Spatial WG (Kilsby *et al.*, 2011). The Spatial WG only provided future weather data under median emission scenario by the time of writing this paper. For a 5km by 5km grid location, 100 sets of 30-year long weather data could be provided. That is, 100 climate change estimates randomly sampled from UKCP09 probabilistic climate change projections were

incorporated into 30-year baseline data (1961 to 1990), i.e. control year data. Totally, 3000 future climate data were generated for the 2020s and 2080s respectively. Then, extremely hot years which included any type of the three heatwaves could be selected from them. Then, 3000 future weather files (i.e. 3000 sample years for the 2020s and 2080s respectively) were produced in EPW format for use in building simulation. The three heatwave criteria (see Table 4) were used to identify external heatwaves from the future weather files. The impacts of future heatwaves on non-air conditioned UK dwellings (i.e. typically naturally ventilated during summer) were predicted via building simulation. The future years containing heatwaves, which were very likely to have a great influence on the risk of internal heat-related mortality, were selected as future HEYs.

Dynamic thermal simulation with 6000 future weather files (i.e. 3000 weather files for the 2020s and 2080s respectively) were carried out using EnergyPlus version 8.8.0 as DesignBuilder® cannot run group building simulation with multiple weather files. The impacts of future heatwaves on occupants' health were assessed based on internal heat-related mortality threshold temperature. Armstrong *et al.* (2011) found the temperatures-mortality relationship for England and Wales. The 93rd percentile 2-day mean temperature was found to be the threshold temperature for risk of heat-related mortality (Armstrong *et al.*, 2011). It could be assumed that the relationship between temperature and heat-related mortality was the same for the external and internal thermal environment (Taylor *et al.*, 2015; Liu *et al.*, 2017; Taylor *et al.*, 2018). The 93rd percentile 2-day mean internal temperature was considered as threshold temperature ($T_{\text{threshold}}^{\text{mortality}}$) for the prediction of internal heat-related mortality in previous studies (Taylor *et al.*, 2015; Liu *et al.*, 2017; Taylor *et al.*, 2018). All-cause deaths during heatwave periods is required to calculate heat-related deaths. Nevertheless, it is hard to obtain such data for future heatwave periods. Hence, this study evaluated influence of future heatwaves (e.g. Heatwave-1, Heatwave-2 or Heatwave-3) on occupants' health by looking at whether internal 2-day mean temperatures ($T_{2\text{-day}}^{\text{mean}}$) exceeded $T_{\text{threshold}}^{\text{mortality}}$. As shown in Figure 2 all of $T_{2\text{-day}}^{\text{mean}}$ caused by external heatwaves were compared with $T_{\text{threshold}}^{\text{mortality}}$ in order to determine whether or not the external heatwaves caused increments in the relative risk of heat-related mortality in the houses.

Figure 1: Creation of future Hot Event Years based on the catastrophic heatwave criterion.

Figure 2: Corresponding internal T_{mean}^{2-day} to external heatwaves, e.g., Heatwave-1, Heatwave-2 or Heatwave-3.

Thermal modelling for UK houses

Building simulation program DesignBuilder® version 5.0.3.007 was used to create thermal models of UK houses. A detached house type was chosen in this study as it is one of the most typical dwelling archetypes in the UK (Allen and Pinney, 1990). Its geometry and floor plan are shown in Figure 3. The houses were modelled with varying building orientations (0° , 90° , 180° and 270°). The details of constructions and fenestrations are presented in Table 1 and Table 2. All the thermal properties were referred to Table 3.49 in Appendix 3.A presented in CIBSE Guide A (CIBSE, 2006). In addition, a few assumptions were made based on previous studies (Liu *et al.*, 2017; Beizaee *et al.*, 2013) for the creation of

thermal models. As UK houses are non-air-conditioned buildings they rely on natural ventilation during hot summer. It was assumed that natural ventilation was triggered when (1) internal temperature was higher than external temperature, (2) internal temperature exceeded 24°C and (3) during occupied hours. It also was assumed that a person was doing light work (i.e. 1.2 met) in living room from 09:00 to 22:00 while a couple was sleeping (i.e. 1.0 met) in the main bedroom from 23:00 to 08:00.

Figure 3: Geometry and floor plan for a typical detached house.

Table 1: Construction details.

	Constructions	U-value (W/m ² K)
External wall	105 mm brickwork outer leaf 100 mm air layer 50 mm EPS Expanded Polystyrene 105 mm brick, inner leaf 13 mm plaster	0.50
Internal partition	13 mm plaster (dense) 215 mm brick, inner leaf 13 mm plaster (dense)	1.79
Internal floor	10 mm plasterboard (ceiling) 200 mm air layer 20 mm timber flooring 5 mm carpet/textile flooring	1.33
Ground floor	500 mm clay underfloor 50 mm EPS Expanded Polystyrene 150 mm concrete roof/floor slab 50 mm flooring screed	0.50
Roof	10 mm concrete roof tiles 1000 mm cold loft space 250 mm min wool quilt 9.5 mm plasterboard (ceiling)	0.16

Table 2: Window and door characteristics.

Constructions		U-value (W/m ² K)
Double glazing	6 mm generic clear glass	2.71 (SHGC=0.70)
	13 mm air	
Window frames	6 mm generic clear glass	3.48
	20 mm polyvinylchloride	
Door	35 mm painted oak	2.25

Results and discussion

The occurrences of three different external heatwaves, i.e., Heatwave-1, Heatwave-2 and Heatwave-3 in 3000 future weather files are presented in Figure 4. On average, Heatwave-1 and Heatwave-2 occurred approximately twice (1.9 times) and three times (2.9 times) respectively in every future weather file for the 2020s while there was only 20% possibility that Heatwave-3 would occur in each future weather file for the 2020s. For the 2080s, the occurrences of the heatwaves would increase to 3.8, 4.3 and 2.5 times due climate change. This could be supported by the statement in the fifth IPCC report (IPCC, 2013) that it is very likely that frequency of heatwaves will increase due to climate change. In addition, among 3000 future sample years generated for the 2020s, 2548 years included Heatwave-1 and 2890 years included Heatwave-2 while 467 years included Heatwave-3; for the 2080s, 2969 years included Heatwave-1, all of 3000 years included Heatwave-2 while 2341 years included Heatwave-3. In short, Heatwave-1 and Heatwave-2 were more likely to occur compared with Heatwave-3.

Figure 4: Averaged occurrences of different external heatwaves in each of 3000 future weather files for the 2020s and 2080s respectively.

The influences of heatwaves on the risk of heat-related deaths were evaluated via dynamic thermal simulations. Internal $T_{2\text{-day}}^{\text{mean}}$ (i.e. living room and bedroom temperatures together) were derived from building simulations with 6000 future weather files (3000 per future time slice, i.e. 2020s and 2080s). The 93rd percentile 2-day mean internal temperature for the 2020s and 2080s, i.e. $T_{\text{threshold}_2020s}^{\text{mortality}}$ and $T_{\text{threshold}_2080s}^{\text{mortality}}$ were 28.8 °C and 32.2 °C respectively. If there were no thermal adaptations, the threshold would be unchanged by the 2080s so that $T_{\text{threshold}_2020s}^{\text{mortality}}$ could be used for the 2080s.

If occupants adapt to warmer climate, however, $T_{\text{threshold}_2080s}^{\text{mortality}}$ should be used for the 2080s.

Table 3 shows number of occurrences of heatwaves found in all of 3000 future weather files by heatwave types. The total occurrences of Heatwave-3 was much fewer compared with other heatwaves. Figure 5 shows internal $T_{2\text{-day}}^{\text{mean}}$ resulted by all heatwaves found in future weather files by heatwave types. As can be observed from Figure 5 not all of heatwaves found in future weather files resulted in the risk of internal heat-related deaths. Median $T_{2\text{-day}}^{\text{mean}}$ given by both Heatwave-1 and Heatwave-2 in the 2020s were below $T_{\text{threshold}_2020s}^{\text{mortality}}$ (i.e. 28.8 °C) while median $T_{2\text{-day}}^{\text{mean}}$ given by Heatwave-3 exceeded $T_{\text{threshold}_2020s}^{\text{mortality}}$. This indicates that Heatwave-3 would be a greater threat to occupants compared with other heatwaves. For the 2080s without thermal adaptations, median $T_{2\text{-day}}^{\text{mean}}$ given by both Heatwave-1 and Heatwave-3 exceeded $T_{\text{threshold}_2020s}^{\text{mortality}}$ (green dash line). With thermal adaptations, however, only Heatwave-3 caused median $T_{2\text{-day}}^{\text{mean}}$ higher than $T_{\text{threshold}_2080s}^{\text{mortality}}$ (blue dash line). This suggested that Heatwave-3 in the 2080s had a catastrophic influence on the risk of internal heat-related mortality even if occupants adapt to warmer climate in the future. Therefore, Heatwave-3 is more extreme than others in terms of its influence on indoor thermal comfort and the risk of internal heat-related deaths.

Table 3: Number of occurrences of each type of heatwave in all of 3000 future weather files.

	Heatwave-1	Heatwave-2	Heatwave-3
2020s	5808	8781	561
2080s	11533	12895	7605

Figure 5: Internal $T_{2\text{-day}}^{\text{mean}}$ caused by three different heatwaves for the 2020s and 2080s. $T_{\text{threshold}}^{\text{mortality}}$ for the 2020s and 2080s were presented as blue and green dash lines respectively. Note the exceedance of the mortality thresholds indicates that the relative mortality risk is likely to increase.

Figure 6 shows the possibilities of deadly heatwaves for Heatwave-1, Heatwave-2 and Heatwave-3 (i.e. P_{HW-1}^{deadly} , P_{HW-2}^{deadly} and P_{HW-3}^{deadly}) in the 2020s and 2080s. Some heatwaves could be seen as non-deadly heatwave which would not lead to increments in the risk of internal heat-related deaths (see Figure 5 above). For instance, among all of Heatwave-1 the ones that caused internal T_{2-day}^{mean} higher than $T_{threshold}^{mortality}$ could be regarded as deadly heatwaves. Percentage of such deadly heatwaves of total occurrences of Heatwave-1 in all 3000 future weather files was considered as possibility of deadly heatwaves, i.e. P_{HW-1}^{deadly} . Again, it was assumed that $T_{threshold,2080s}^{mortality}$ would be equivalent to 28.8 °C if there were no human thermal adaptations while $T_{threshold,2080s}^{mortality}$ would be increased to 32.2 °C if there were human thermal adaptations. For the 2020s and 2080s (without human thermal adaptations), P_{HW-3}^{deadly} were 96% and 99% respectively, suggesting that almost every single Heatwave-3 found in 3000 future weather files would increase the risk of heat-related mortality. Values of P_{HW-1}^{deadly} and P_{HW-2}^{deadly} were much smaller than P_{HW-3}^{deadly} . For the 2080s when $T_{threshold,2080s}^{mortality}$ increased to 32.2 °C (i.e. with human thermal adaptations), P_{HW-1}^{deadly} and P_{HW-2}^{deadly} were 4% and 1% respectively, indicating that it was very unlikely that Heatwave-1 and Heatwave-2 would have an influence on the risk of internal heat-related deaths. Therefore, it would be inappropriate to use them for rigorous building resilience assessment. Hence, both Heatwave-1 and Heatwave-2 criteria (see Table 4) would be unsuitable for selecting future extreme years from 3000 future sample years generated by Spatial WG. In contrast, Heatwave-3 criterion seemed more appropriate than others in identifying deadly heatwaves in 3000 future sample years as almost every Heatwave-3 was found to have a great influence on the risk of heat-related mortality. Hence, the HEYs could be selected from future sample years based on the Heatwave-3 criterion. However, if occupants were able to adapt to warmer indoor environment in the 2080s, P_{HW-3}^{deadly} for the 2080s would decrease to 67%. This could be a concern that the Heatwave-3 criterion might not ensure HEYs containing deadly heatwaves.

Conclusion

Previous creations of future weather files (CIBSE, 2016; Eames *et al.*, 2011; Liu *et al.*, 2016; Watkins *et al.*, 2012) for assessing overheating risk and testing building adaptations against warming climate did not take account of deadly heatwaves. So, none of the weather files are suitable for a rigorous evaluation of building resilience to future heatwaves. This work generated fresh insight into the creation of future HEYs that contain deadly heatwaves. As the traditional heatwave definitions focused on the outdoor abnormally high temperature for a certain period rather than the influence of heatwave on

Figure 6: Possibilities of deadly heatwaves for the 2020s and 2080s (with and without human thermal adaptations).

indoor thermal comfort (Xu *et al.*, 2016), it was unknown which one would be a great threat to occupants living in naturally ventilated buildings. Three widely accepted heatwave definitions from WMO, UKCP09 and UK Heat-Health Watch Service were used to extract heatwaves from future climate data provided by Spatial WG (Kilsby *et al.*, 2011). Their impacts on the risk of internal heat-related deaths were examined in this paper. It was found that almost every heatwave selected based on Heatwave-3 definition could have a deadly effect on occupants' health. In contrast, heatwaves selected based on Heatwave-1 and Heatwave-2 criteria had little impact on the risk of heat-related mortality. Therefore, Heatwave-3 criterion would be more suitable for the creation of future HEYs from future synthetic climate data. If people will be able to adapt to warmer climate as fast as warming climate, threshold temperature for the risk of heat-related mortality would also increase. In this case, it is unlikely to ensure the heatwaves selected based on Heatwave-3 would have an influence on the risk of internal heat-related deaths. Hence, an alternative heatwave criterion should be proposed for the creation of future HEYs when taking

thermal adaptations into account. Or various heatwave definitions reviewed by (Xu *et al.*, 2016) could be examined in terms of their impacts on the risk of internal heat-related mortality. In addition, more typical UK dwelling archetypes will be considered in future work to evaluate building resilience against future heatwaves at a regional or national scale. Given appropriate heatwave definitions for indoor thermal environment and localized future climate data, future HEYs could be produced for any location in the world. Building practitioners will be able to find out appropriate building adaptations to reduce the relative risk of internal heat-related mortality via dynamic thermal simulation with future HEYs. Therefore, future HEYs will have a profound effect in ensuring safe indoor thermal environment against changing climate.

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Table 4: Heatwave definitions.

Heatwave	Heatwave definitions	References
Heatwave-1	Tmax >5 °C above the average daily Tmax of the period 1961-1990 for at least six consecutive days (throughout the year)	(Frich <i>et al.</i> , 2002)
Heatwave-2	Tmean >3 °C above the average daily Tmean of the period 1961-1990 for at least six consecutive days (May to October)	(Perry, 2006)
Heatwave-3	Daily temperatures exceed the threshold Tmax of 32 °C for daytime and Tmin of 18 °C for overnight for at least two consecutive days (June to September)	(UK Met Office)