Efficient Summertime Overheating Analysis Using Decomposed Weather Files

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Abstract

Overheating within European buildings is a big problem and the building design plays a significant role in any health-related outcomes

We show that heatwaves can be extracted from historic data based on how they affect buildings, rather than how they affect the external temperature. We propose a simple way of rating heatwaves based on the severity of their effect on the *internal* environment.

Background

Buildings cannot be tested against overheating in the real world, so they are tested via computer simulation. We can test buildings for overheating in many ways (BSI, 2007; Matt Eames, Wood, & Challenor, 2015; Fanger & Others, 1970; Jendritzky, de Dear, & Havenith, 2012; Stainforth, Downing, Washington, Lopez, & New, 2007). There are many different metrics used for overheating and there are many ways in which these metrics can be triggered:

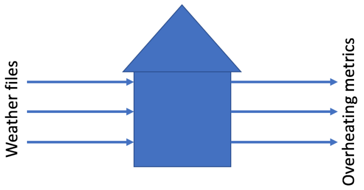

Figure 1: 'Inputs and outputs' to the building model regarding overheating

In the UK, the weather data used to test buildings are typically design summer years (DSY) (M. Eames, 2016). This data is usually one year long and contains several periods of hot weather. However, these hot periods are only a small proportion of the year, so there is clearly a large amount of redundancy in the data.

It is not computationally efficient to run a whole year's worth of weather data to test the building's response to short periods of hot weather. Much of the computation time is wasted on periods of the year that won't result in overheating.

Testing a single weather-year also restricts the different types of heatwave that can be tested. Heatwaves vary in duration and severity. The diurnal temperature range can also vary as well as wind speed, direction and humidity. It is therefore clear that a single weather year of data cannot sufficiently test a building for all the different types of heatwave that might be possible.

The type of heatwaves in the weather file should depend on the climate and the building being tested. Most recent research into heatwaves think of the severity as the effect of the heatwave on the external air temperatures. However, it has been shown that effects on the *internal* environment of buildings can vary greatly depending on the building itself and the metrics used to measure it (ME Eames, 2014).

In this paper, we present a methodology for the extraction of heatwaves from weather data. The aim of this is to show that simple overheating metric results can be re-created by using only the heatwave portion of the year. Having demonstrated that this can be achieved successfully, we then apply a simple rating method using the *duration* and *severity* of the heatwave to identify similar heatwaves. We then compare heatwaves that have a similar duration and severity to see if they have a similar effect on the overheating of a range of different building types.

The overall aim of our work is to confirm that heatwaves can be isolated and still have the same effect on the overheating metrics. We also aim to determine whether the severity of the heatwaves is correlated with the severity of the overheating metric for a range of different buildings.

Motivation

Our work is motivated by the need to create buildings that are both comfortable and heathy for their occupants. Since most people in Europe spend more the 80% of their time indoors (Klepeis et al., 2001; Lader, Short, & Gershuny, 2005) the design of our buildings has a significant impact on peoples' health and wellbeing (Brucker, 2003; Jentsch, Bahaj, & James, 2008; Kovats & Kristie, 2006).

The are many projections that predict that the severity and regularity of heatwaves will increase in the future (Parmesan & Yohe, 2003). Because of this, overheating in buildings is likely to increase (Banfill et al., 2012). It is therefore important that we design buildings that are more resilient to these heatwaves.

Previous work

Future weather files

One way of designing more resilient buildings is to test them against future weather patterns. This is achieved by creating synthetic weather files based on the future climate predictions.

In the UK, this has led to the creation of new Design Summer Years (DSYs) (M. Eames, 2016; Hacker, Capon, & Mylona, 2009). These DSYs aim to provide a 'stress test' as they contain several different heatwaves of different severity.

Eames has extended the work of Jensch et al. (Jentsch et al., 2008) on the development of DSYs for future-proofing buildings against climate change. Eames rates the heatwave severity using Generalised Extreme Value (GEV) distributions (Coles, 2001; M. Eames, 2016). The extreme value distribution allows the 'return period' of an event to be calculated.

Return periods are measures of how often (on average) we expect an event to occur. The longer the return period, the more extreme the event is. Eames uses to define weather events of different severity (M. E. Eames, Ramallo-Gonzalez, & Wood, 2015). Porritt et al have identified the need to ensure that both new and old buildings are tested against their performance during heatwaves of different severity (Porritt, Shao, Cropper, & Goodier, 2011).

Coley and Kershaw have looked at the relationship between average internal and external *climatic* temperatures. Their work has shown that the relationship between their two values is largely linear (Coley & Kershaw, 2010). Furthermore, they have shown that the linear relationship depends on the characteristics of the specific building.

Some buildings amplify the external climate more than others. Because of this, we can't assume that rating heatwaves based on their *external* severity is a good way to predict their *internal* severity for all building types.

There has been relatively little research into how heatwaves could be rated according to the influence that they are likely to have on internal temperatures.

Overheating criteria

One major barrier to the development of a rating method are the number of different ways to measure overheating. These include (but are not limited to);

- Number of Weighted Cooling Degree Hours based on the mean radiant temperature ($WCDH_{rad}$);
- Number of hours greater than 25 degrees (hrs > 25);
- Number of hours greater than 28 degrees (hrs > 28);
- Number of hours where the predicted mean vote (PMV) is greater than 0.5 (PMVH);
- Number of hours where the internal temperature exceeds the comfort temperature by more than 3 degrees (hrs > CT+3);
- Number of hours where the universal thermal comfort index (UTCI) is greater and 25 degrees (UTCIH);
- Number of Weighted Cooling Degree Hours based on the UTCI temperature ($WCDH_{UTCI}$);

Eames has looked at overheating events of different severities from the perspective of *internal* overheating criteria above (M. E. Eames et al., 2015). Using *extreme value theory*, a 1:7 year (near extreme) and 1:21 year (extreme) events for different overheating metrics was determined. The results showed that the 'extremeness' of the year is dependent on the choice of overheating variable. The extreme and near extreme overheating years shown for London are:

Table 1: Extreme (1:21) and near-extreme (1:7) overheating years for London

	HRS > 25	HRS > 28	CT+3H	$WCDH_1$	PMVH	UTCIH >25	$WCDH_2$
Near extreme	2013	1983	1983	2013	2013	2003	2005
Extreme	2006	1976	2006	1995	2006	2006	1976

These results show that the '*extremeness'* of a weather file is dependent on the internal comfort parameter that we chose to measure it. This makes it difficult choose an internal overheating metric based on internal comfort.

Unfortunately, we don't have a good way to choose between these internal metrics. However, given that our work focuses on isolating and rating overheating periods, it only matters that we used the *same* overheating metric throughout our analysis.

Although we could have chosen other methods, we have based our overheating metrics on the CIBSE TM52 guidelines on overheating in European buildings. The CIBSE criteria were chosen because there are methods of rating both the severity and the duration of the heatwaves.

CIBSE overheating criteria for European buildings

CIBSE TM52 was released in 2013 and proposes three overheating criteria for European buildings:

1. The number of hours where the internal operative temperature is above the maximum acceptable temperature (H_e)[1]
2. The daily weighted exceedance (W_e).
3. The maximum operative temperature (T_{upper})

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[1] Where H_e stands for *hours of exceedance*

These criteria are intended to minimise overheating over a broad range of possible overheating events.

We use the first two criteria because they both have a time-series component (hours of exceedance) and a severity component (weighted exceedance). These criteria allow us to measure the internal duration and severity.

Method

To rate the overheating based on the internal overheating criteria, we need to take account for the obvious fact that the internal temperatures will be different across different building types. To do this, we run each of the weather years though an ensemble of 100 buildings.

The following sections shows how we use the output data and the CIBSE criteria to isolate the heatwave data. We also show details of the office building that we use for this assessment.

The heatwave extraction method

We detect the heatwaves using the internal temperature time series for 100 different office buildings. For each weather file, this creates 100 different time-series measures of ΔT (where ΔT measures how far above the maximum acceptable temperature the internal operative temperature is). If ΔT is greater than 0 for any hour in any building, we define this as a heatwave.

We extracted the heatwave data by performing a Hilbert-Huang (HH) empirical mode decomposition on the mean radiant and dry bulb temperature time series of each weather file[2] (Huang et al., 1998). This method is an efficient way of extracting the trend data from the noise.

An example of an annual temperature 'trend' and separated ‘noise’ are shown in Figure 2. The noise functions are called intrinsic mode functions (IMFs).

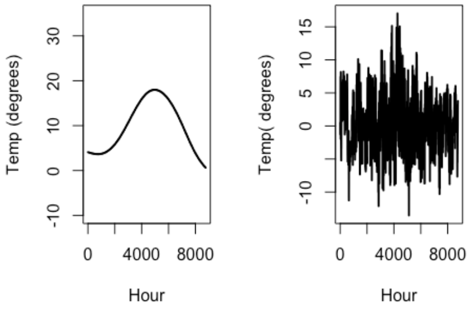

Figure 2: Example of trend (left) and IMF data (right) for Norwich UK DSY3

The full weather file time series is given by:

$$\text{Time series} = \text{Trend} + \sum_{j=1}^{k} \text{IMF}_k \qquad (1)$$

To isolate the heatwaves, we only include the IMFs when a heatwave is present. If there is a heatwave at time $= i$, then $H_i = 1$, else $H_i = 0$:

$$\text{Time series}_i = \text{Trend}_i + \{\sum_{j=1}^{k} \text{IMF}_{i,k}\} H_i \qquad (2)$$

We use this method to be able to separate the heatwave data (sum of the IMFs) from the general trend.

Our idea is to identify a heat wave and superimpose the heatwave on the trend series. We did this to ensure that, before each heatwave, the building would have a sufficient warm-up period. We are aware that it is excessive to include the whole years’ worth of warm up data for a heatwave that might only last a few days. However, simulating the building in this way avoided the need to research the minimum warm up time (which may vary between different building types).

CIBSE Criteria A: Heatwave duration

If $\Delta T > 0$ is greater than 0 for any of the 100 buildings, then we classify that section of the weather year as a heatwave.

ΔT measures the exceedance of the maximum acceptable internal temperature. It is calculated on every time step of the simulation and is related to the operative temperature T_{op}. The operative temperature is in turn based on the air temperature T_a and the mean radiant temperature T_r:

$$T_{op} = \frac{T_a - T_r}{2} \qquad (3)$$

As discussed, ΔT measures the exceedance of the maximum acceptable temperature T_{max}:

$$\Delta T = T_{op} - T_{max} \qquad (4)$$

The maximum acceptable temperature T_{max} is dependent on the *running mean* temperature T_{rm};

$$T_{max} = 0.33 T_{rm} + 21.8 \qquad (5)$$

where T_{rm} is defined as;

$$T_{rm} = (1 - \alpha) T_{od-1} + \alpha T_{rm-1} \qquad (6)$$

Where T_{od-1} is the outdoor daily mean temperature for the previous day, T_{rm-1} is the running mean temperature for the previous day and α is an empirically derived

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[2] note that all other weather variables, such as wind speed and direction, stayed the same

coefficient (typically 0.8). These equations can be used to derive ΔT for each timestep.

CIBSE Criteria B: Heatwave intensity

We define the heatwave's *internal* intensity using the daily weighted exceedance, W_e. Although this is defined as the weighted exceedance, it is more accurately described as the cumulative exceedance over a given day. The units are in hours-Kelvin. It can be visually defined as the sum of the grey area (shown in Figure 3) over a 24-hour period:

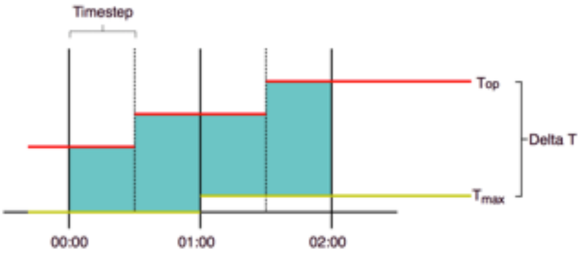

Figure 3: Visual definition of weighted exceedance

The DWH_e is a measure of the intensity of the heatwave as it is experienced *internally*.

Heatwave sources: the new CIBSE DSYs

To extract heatwaves, we need weather data to extract them from. We used the recently-updated CIBSE design summer year (DSY) data for the UK (M. Eames, 2016). These files contain hot weather events of varying intensities:

Hot event type	DSY file
Moderate (1:3)	DSY1
Near-extreme (1:7)	DSY2
Extreme (1:21)	DSY3

Each DSY weather file is a full year of weather data containing either moderate, near-extreme or extreme hot weather events.

A simple metric is used to define overheating in each year. The metric considers the weighted exceedance of external temperatures above the 93rd centile of dry bulb temperature at the location. The threshold temperature is the temperature at which the deaths due to overheating can be attributed. A moderate DSY is considered as a 1:7 year (DSY1). Other DSYs were determined by having longer return periods so were therefore less frequent but also contained overheating events with different signatures. DSY2 contained an overheating event which was longer than any event in DSY1 while DSY3 contained an event which was short but more intense than any event in DSY1. In this work, we will consider all three DSY types.

These weather files include 14 locations across the UK namely, Birmingham, Cardiff, Edinburgh, Glasgow, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton, and Brize-Norton.

Heatwave extraction

The heatwave extraction method works by defining a heatwave as any period where $\Delta T > 0$ for *any one* of the 100 buildings. This process is outlined in Figure 4.

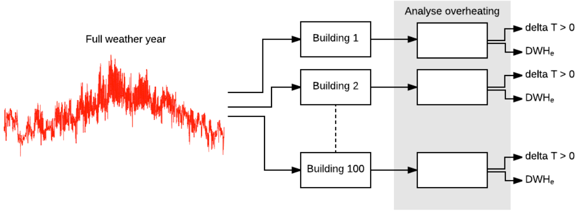

Figure 4: Full weather year calculation process

Clearly the periods where $\Delta T > 0$ will vary depending on the building. Because each weather file is run through 100 buildings, the heatwave periods are likely to differ slightly between buildings. Figure 5 shows these variations in heatwave periods for Newcastle UK DSY2.

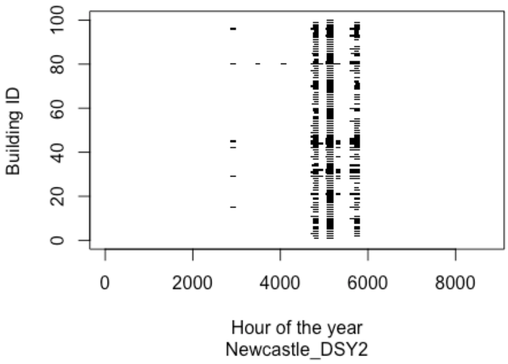

Figure 5: Newcastle UK DSY2 trace of 100 buildings showing zones where Delta T is greater than 1

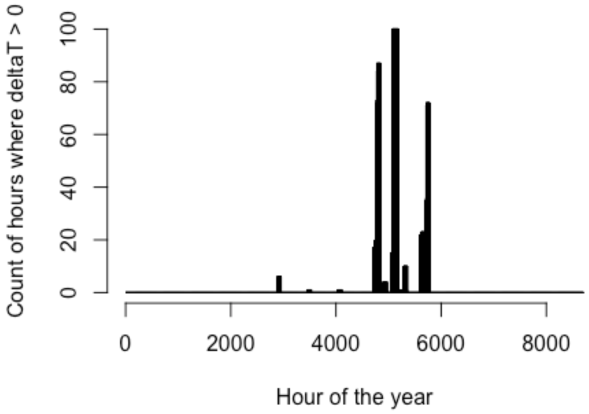

Figure 6: Newcastle UK DSY2 histogram showing the frequency of where delta T > 0 for 100 buildings

The results in Figure 5 and Figure 6 show that most 'heatwave' periods are common across all buildings. However, some buildings experience heatwaves when others don't.

Heatwave extraction verification

Since we are trying to extract heatwaves that have the potential to affect any building, we treat *any* exceedance of $\Delta T > 0$ for *any building* a heatwave. We then calculate the *intensity* and *duration* statistics for this heatwave.

Since we also want to investigate whether the heatwave will trigger the same overheating results when the heatwave is isolated, we also run the isolated heatwave through the 100 building models as outlined in Figure 7.

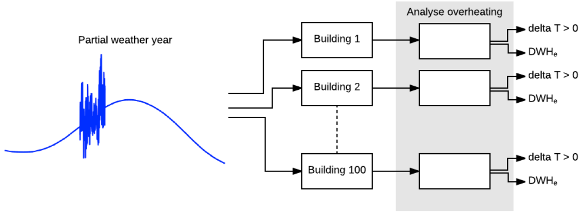

Figure 7: Extracted heatwave verification process

Definitions of heatwave duration and intensity

The duration of each heatwave is the period (in hours) between the start and the end of the heatwave. The heatwave intensity rating (HIR) is defined as:

$$\mathrm{HIR} = \sum_{m=1}^{100} \{ \sum_{n=1}^{days} \frac{DWH_{e,n,m}}{\mathrm{days}} \} \qquad (7)$$

The HIR is the average of the daily weighted exceedance averaged over 100 buildings.

Testing the rating method

The hypothesis we are testing is that two heatwaves with similar intensities and durations should have similar effects on the overheating criteria (for the same building). Similar heatwaves are where;

$$\mathrm{Duration}_{\mathrm{heatwave\ 1}} \approx \mathrm{Duration}_{\mathrm{heatwave\ 2}} \qquad (8)$$

and;

$$\mathrm{HIR}_{\mathrm{heatwave\ 1}} \approx \mathrm{HIR}_{\mathrm{heatwave\ 2}} \qquad (9)$$

If we can demonstrate that, for buildings x and y, that Criterion $A_x \simeq$ Criterion A_y and Criterion $B_x \simeq$ Criterion B_y for both extracted heatwaves, this is a positive indication that our method has some use for rating the effect of heatwaves on internal temperatures.

Building type used for testing

The building model used in the research was a simple office building:

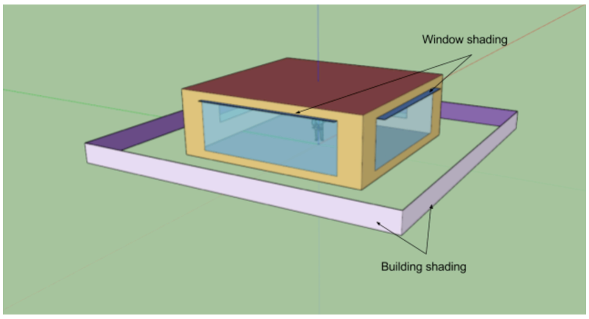

Figure 8: Office building used in the model

We generated 100 buildings based on this simple design by varying the following design parameters[3]:

- Aspect ratio
- U-values of the walls, roof and windows
- Glazed percentages (north, south, east and west)
- Thickness of the roof concrete (used for changing the thermal mass)
- Window overhangs (used to provide shading)

The 100 buildings were generated using a Latin hypercube sample of the variables above (ranges for these variables are given in the appendix). We also assumed that the office was occupied by 5 people, the lighting has a power density of 5 watts per m^2, and the activity of each person is equivalent to 80 watts. No temporal shading is included.

The occupancy schedule model was based on a typical occupancy profile for an office:

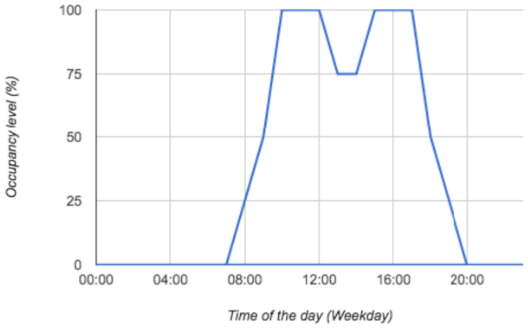

Figure 9: Occupancy schedule used in the model

The external construction was:

- Wall construction: 100mm brick / insulation / concrete
- Roof construction: Tiles / Membrane / insulation / plasterboard
- Floor construction: Insulation / Concrete / Cavity / Chipboard / Carpet
- Windows construction: Low emissivity double glazing (6 mm/13 mm/6 mm) Argon filled (with 25% equivalent openable area)

More detailed information about the building's construction is in the appendix (Table 4).

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[3] See appendix for the ranges of each variable used.

Results

Verifying the heatwave extraction method

The full weather files and partial weather files (i.e. files with heatwaves only) were tested on the 100 buildings. Each 100-building set was tested with 42 weather files of both types (84 in total).

The results for the full and partial weather files are compared for each of criterion A and B in Figure 10 and Figure 11.

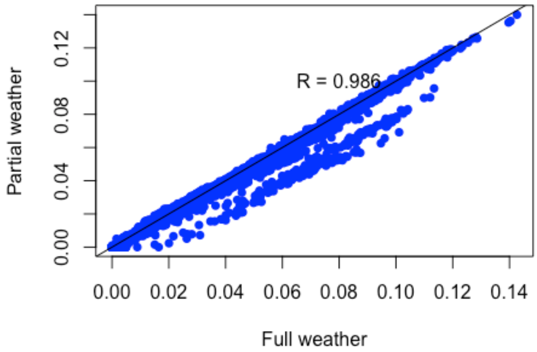

Figure 10: Comparison of criteria between full and partial weather files: Criterion A

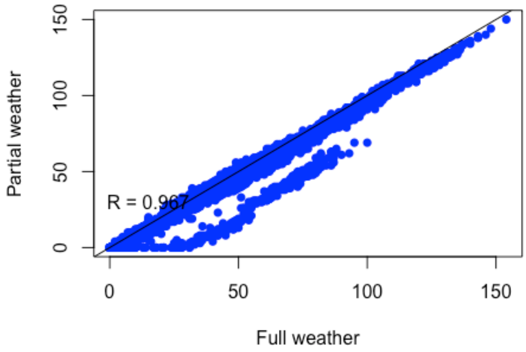

Figure 11: Comparison of criteria between full and partial weather files: Criterion B

Comparing the duration and intensity of extracted heatwaves

Figure 12 shows how the duration of the average daily weighted exceedance (in this case summed for all buildings) is correlated to the heatwave's duration. Similar heatwaves are closer together. Longer and more intense heatwaves are situated nearer to the top right:

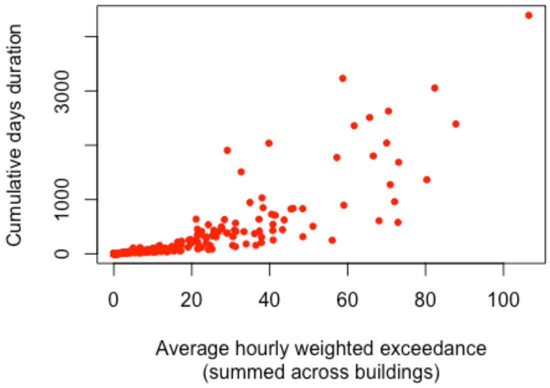

Figure 12: Average exceedance vs. intensity

We expect similar heatwaves extracted from two different files to have similar effects on all 100 buildings. As an initial investigation, we picked the similar as described in Table 2 for comparison.

Table 2: Heatwaves used in the comparison

	Start Hour	**Stop Hour**	**Intensity**
Belfast DSY2	4591	5025	Low
Birmingham DSY2	4279	4517	Low
Southampton DSY1	4373	5023	Med
Plymouth DSY3	4222	4542	Med
Manchester DSY3	4752	5670	High
Birmingham DSY3	4776	5671	High

We ran each of these heatwaves through the 100 buildings. For each building's heatwave pair, we calculated both the CIBSE A and CIBSE B criteria. The results are shown in Figure 13, Figure 14 and Figure 15below.

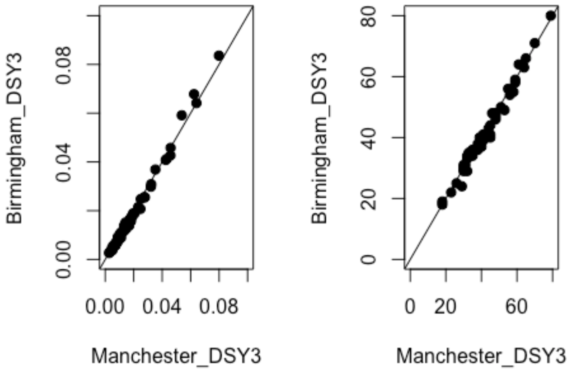

Figure 13: High intensity heat waves: Criteria A left, criteria B right.

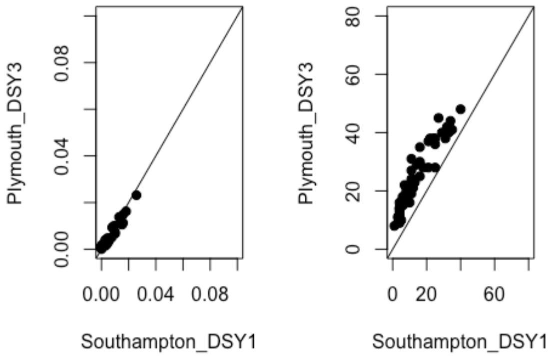

Figure 14: Medium intensity heat waves: Criteria A left, criteria B right.

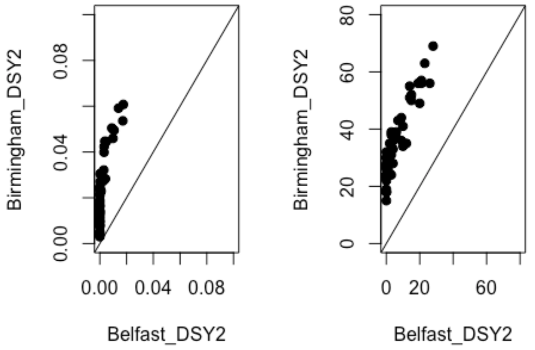

Figure 15: Low intensity heat waves: Criteria A left, criteria B right.

Conclusions and discussion

The results show that the extraction method works well. There are strong correlations (R = 0.986 and R = 0.967) between the full and partial weather files heatwaves for both the CIBSE A and CIBSE B criteria. However, in both Figure 11 and Figure 12 there are a significant number of results that are outliers from the line of best fit:

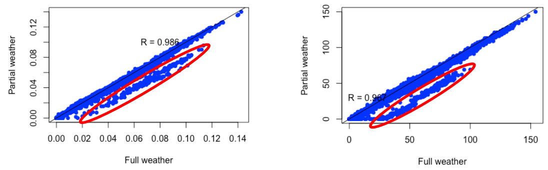

Figure 16: Outliers (circled red) when comparing partial to full weather files for the CIBSE A (left) and CIBSE B (right) criteria.

Investigating these outliers will be the subject of future work. However, these results show that there is potential to reduce the redundancy of information in current weather files.

The results have also shown that more intense (i.e. hotter) heatwaves tend to be longer (see Figure 12) and that similar heatwaves tend to have similar results when tested over a range of buildings (Figure 13 - Figure 15).

The comparison between the example pairs of similar intensity shows good correlation for heatwaves that are classified as *high* intensity (Figure 13). The results for medium intensity heatwaves are slightly less correlated (Figure 14) and there are significant differences between heatwaves of low intensity (Figure 15). However, we need to perform more detailed (and structured) comparisons to draw definitive conclusions.

Our initial results show that our heatwave extraction and rating system is reasonably consistent. However, these results only apply to the single building designs we have chosen. Our conclusions may not necessarily apply across a range of different building types, or even climates. Further work is therefore needed.

If this research can be suitably developed, the principles could be used to develop more efficient and potentially more comprehensive weather files. However, before this is possible, a better understanding of the effect of overheating on people should be gained.

The CIBSE criteria used in our research are usually used for compliance purposes, and do not *necessarily* relate well to human comfort and health. Further work in this area should expand the analysis to include a broader range of overheating criteria.

Our method should also be tested in different climates. Since our results are based on the CIBSE overheating criteria for *European* buildings, this method may only be useful for buildings in this climate. However, the concept of rating heatwaves based on their effect on buildings could be developed using similar methods.

Other opportunities for further work include exploring:

- heatwaves in future climates;
- generating synthetic heatwaves for better stress tests; and
- analysing heatwaves (and their effects) from historic data.

Appendix

Table 3: Variable ranges used in the building model

Real Name	**Min**	**Max**
Number of Floors	1.00	2.0
Number of adiabatic walls	0.00	2.0
Aspect ratio	0.50	1.0
U-value walls ($Wm^{-2}K^{-1}$)	0.10	0.5
U-value roof ($Wm^{-2}K^{-1}$)	0.10	0.5
Air changes per hour (ACH)	1.00	6.0
Glazing N/S/E/W (%)	0.00	0.9
Window U-value ($Wm^{-2}K^{-1}$)	1.00	2.0
No of internal partitions	1.00	5.0
Shading height N/S/E/W (m)	0.10	5.0
Electricity usage ($Wm^{-2}K^{-1}$)	5.00	15.0
Concrete thickness (m)	0.05	0.5
Thermal absorption (ratio)	0.10	0.9
Overhang north N/S/E/W (m)	0.10	1.0

Table 4: Properties of the materials used in the building

Name	Thickness (m)	Conductivity (W.m^{-1}K^{-1})	Density (kgm^{-3})	Specific heat (Jkg^{-1}K^{-1})
Membrane	0.0001	1.000	1100	1000
Plasterboard	0.0125	0.210	700	1000
Floor insulation	0.1100	0.025	700	1000
Concrete floor	0.1000	2.300	2300	1000
Chipboard	0.0200	0.130	500	1600
Carpet	0.0100	0.040	160	1360
Tiles	0.0127	0.840	1900	800
Concrete	0.2350	1.400	2100	840
Wall insulation	0.0840	0.030	43	1210
Roof insulation	0.0670	0.030	43	1210
100 mm brick	0.1000	0.890	1920	790
Brick partitions	0.0040	0.890	1920	790

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