Climate Change and Buildings:

The Impact on Human Health

Submitted by Edward Shorthouse to the University of Exeter

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

The health risks posed by hot weather are growing as increasingly frequent extreme weather is brought about by climate change. People spend upwards of 80% of time indoors and so human health is largely dependent on the internal environment of buildings. In the building industry engineers currently design buildings for high-energy performance by maximising heat retention, and whilst this may be effective in cold winters, it can lead to unbearable indoor conditions in hot summers. Thermal comfort inside buildings is a well-discussed topic both in industry and academia, but absolute peak thresholds, especially for heat stress still require development. In this thesis the outcomes of research into the effects of current and future hot weather on the heat stress of occupants inside buildings are presented. Hot weather data from the current climate and mortality rates are compared and several temperature metrics are analysed with respect to health risk forecasting performance, so that peak threshold limits for human health indoors are established for the building design industry. Reference weather data used in building simulations for health assessment is currently chosen based on air temperature alone. In this thesis new reference weather data is created for near-extreme and extreme weather and for current and future climates, based on the peak threshold metric research and future weather analysis. By 2050 hot weather reference years currently occurring once every seven years could become an annual occurrence, and by 2080 extreme hot weather reference years currently occurring once in twenty-one years could become an annual occurrence. Computational fluid dynamics is then used to simulate the internal heat stress inside a building model, and a surrogate model is created to

emulate heat stress levels for full calendar years of future climates for several UK locations. It is envisaged that the results presented in this thesis will help inform the industry development of new reference data and aid better building design.

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List of equation terms

ΔT_s	Temperature of Earth's surface
λ	Climate sensitivity parameter
RF	Radiative forcing parameter
H	Internal heat production in the human body
E_d	Heat loss by water vapour diffusion through skin
E_{sw}	Heat loss by evaporation of sweat from skin surface
E_{re}	Latent respiration heat loss
L	Dry respiration heat loss
K	Heat transfer from skin to outer surface of clothing
R	Heat transfer by radiation from clothing surface
C_l	Heat transfer by convection from clothing surface
T_{rm}	Running mean daily average outdoor air temperature
T_{mean-1}	Average temperature of the previous day
T_c	Comfort temperature.
T_{re}	Rectal temperature
HR	Heart rate
T_{app}	Apparent temperature
T_{air}	Air temperature
T_{dewpt}	Dew point temperature
Tr	Mean radiant temperature
va	Air velocity
pa	Vapour pressure
$T_{operative}$	Operative temperature

T_{max}	Maximum temperature threshold
T_{solar}	Solar radiative temperature
α_m	Fractional change in monthly mean value
$\Delta\bar{x}_m$	Change in the monthly mean of the variable
ρ	Density
μ_t	Viscosity
P_b	Buoyancy
Q	Vector of conserved variables
F	Vector of fluxes
V	Volume of control volume element
A	Surface area of control volume element
$m(x)$	Mean of *x*
$\sigma^2 c(x,x)$	Covariance of *x*
θ	Smoothness range parameter
d	Emulator input dimensions

List of acronyms

ANN	Artificial Neural Networks
ASHRAE	American Society for Heating, Refrigeration & Air-conditioning
BADC	British Atmospheric Data Centre
BB101	Building Bulletin 101
CDH	Cooling Degree Hours
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institute of Building Services Engineers
DEFRA	Department for Environment, Food and Rural Affairs
DSY	Design Summer Year
EPBD	Energy Performance of Buildings organisation
EVM	Eddy Viscosity Model
FVM	Finite Volume Method
GEV	General Extreme Value distribution
GPE	Gaussian Process Emulation
HSI	Heat Stress Index
HVAC	Heating, Ventilation and Cooling
IPCC	International Panel on Climate Change
LHS	Latin Hypercube Sampling
ONS	Office of National Statistics
PDF	Probability Density Function
PSI	Physiological Strain Index
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied

RANS	Reynolds-averaged Navier Stokes
RCP	Representative Concentration Pathway
RF	Random Forest
SAP	Standard Assessment Procedure
STL	Stereoscopic Lithography
SVM	Support Vector Machines
TAPP	Apparent Temperature
TRY	Test Reference Year
UHI	Urban Heat Island
UKCIP	UK Climate Impacts Programme
UTCI	Universal Thermal Climate Index
WCDH	Weighted Cooling Degree Hours

1 Introduction

If we knew what it was we were doing,

it would not be called research.

Albert Einstein

1.1 Background

In developed countries people spend around 80% of their time indoors. Homes, offices and public indoor spaces are all currently designed to keep people thermally comfortable based on weather data for today's climate, yet buildings should have a lifespan of at least a century, when climate change has long since caused increases in average temperatures, and extreme weather such as heat waves are a common occurrence. Overheating in buildings is a growing issue as the climate changes and warmer weather is predicted. Meanwhile construction methods and materials are being designed to increase thermal performance, potentially exacerbating the risk of overheating in future summer weather. In the UK the Chartered Institute of Building Services Engineers (CIBSE) regulates overheating by setting indoor air temperature thresholds, and engineers comply by assessing thermal performance at the design stage. Using computer models of buildings, engineers use sample reference years of external weather data from the closest weather station to the construction site and simulate the thermal effect on the building. Thermal comfort assessments are an essential part of the design process in building construction, which in the UK involves using summer weather reference data called design summer years (DSYs) in building simulation models. However, the DSY creation methodology has been shown to be inaccurate, as it is based on air temperature alone, unable to account for extreme weather and is unsuitable for future climates.

Building engineers are faced with a difficult problem: how to design habitable spaces that conform to planning constraints, building regulations and low levels of energy use, whilst at the same time making them comfortable for people to live in for current and future climates. The study of thermal comfort and heat stress caused by future hot weather is necessary to give architects and engineers a clear understanding of the issues they need to overcome in designing future buildings, and retrofitting current ones to cope. New overheating metrics could take advantage of all the environmental weather variables that affect thermal comfort, and that are currently collected at weather stations, whilst reference weather files for future conditions could be produced, ranked according to new overheating metrics, so that building designers could test for overheating in extreme weather and in future climates. One of the goals of this thesis is to develop that work.

To fully analyse heat stress in the indoor environment airflow, heat transfer and humidity should all be considered, since air temperature alone does not provide a fully accounted metric for assessing thermal comfort. Computational fluid dynamics can be used to simulate heat and fluid transfer to offer localised internal heat stress levels with high accuracy. CFD simulations are computationally costly and are usually restricted to research purposes only, so using air temperature as a metric, albeit imperfect, is often deemed adequate enough for thermal assessment. This thesis tackles both the issue of devising a full description of indoor thermal performance and the CFD computational cost hurdles, by creating a surrogate model to emulate CFD simulation results of a complete thermal stress parameter within an indoor space.

1.2 Research Question

Climate change will have a significant impact on building design, energy usage and the internal environment, not just in the UK but around the world. Current estimates predict that changes in temperature could be large enough to cause severe discomfort and have detrimental effects on human health. Although climate change projections suggest an alarming rise in global mean temperatures the predicted effect on weather is far greater. Most assessments of overheating in domestic building design practice only contain static statistics such as “percentage of occupants dissatisfied”, which do not account for the time-varying nature of the problem and therefore cannot be used to assess vulnerability, morbidity or mortality. CIBSE’s TM52 provides a maximum acceptable temperature that is related to the comfort temperature, but this is not an indicative temperature at which health deterioration occurs. In what ways could we develop our understanding of the impact of future extreme weather on buildings and their occupants, where it is clear that a warming climate will increase the risk of overheating in domestic buildings, and what metrics, guidance and best practice for the building design industry could be developed from a scientific approach to learning how human health could be impacted by hot conditions inside buildings? This thesis will address the above questions with relation to the design of new domestic homes without mechanical cooling.

1.3 Thesis Outline

Chapter 2 is an overview of climate change and future climate projections. This chapter investigates the radiative forcing methods used by the International Panel on Climate Change (IPCC) to evaluate the effect of emissions, and then looks at extreme weather and the growth trends of heat waves in particular, since hot weather will form a key part of the investigation in this thesis of the health impacts of climate change in buildings.

Chapter 3 follows with a study of thermal discomfort and human heat stress. Traditional concepts of the effects of hot weather on health are explored, and new heat stress metrics are identified, representing the equivalent temperature that the human body actually feels.

Chapter 4 continues with a study of the impact on health caused by heat waves and hot days from the current climate. Mortality data collected from the Office of National Statistics (ONS) is compared with current and historic hot weather for different UK locations. Using the heat stress metrics and heat wave definitions investigated in chapter 3, the temperature metric that best predicts significant excess deaths in hot weather is identified, and temperature thresholds for the indoor environment are established.

Chapter 5 begins with a study of future probabilistic weather. Future weather, created from climate projections is analysed for extreme thermal conditions, and growth trends in hot weather frequency and intensity are presented. New methodologies for creating key reference weather data used in building design and thermal performance tests are also studied. Using these methods, new reference data for near-extreme and extreme weather conditions in current and future climates is created and presented using the heat stress metric established in chapters 3 and 4.

Chapter 6 is a computational fluid dynamics (CFD) analysis of the thermal response of a building in current and future weather conditions. The heat stress metric established in chapter 4 is coded into a CFD solver, and a simple, naturally ventilated building model is created. The internal thermal environment is simulated, driven by outdoor weather conditions, and a surrogate model is created to rapidly emulate internal heat stress conditions within the building model for any weather. Finally, plots are shown for the actual daily heat stress levels inside a building model for full calendar years of future climates in different UK locations.

2 Climate change and extreme weather

2.1 Climate change

2.1.1 Climate change projections and atmospheric emissions

Earth's future climate and the predicted changes that it will undergo are well understood and widely discussed. It is clear that even if human intervention is successful enough to mitigate against this change to avert some of the more extreme projections, we will still experience a significant shift in future climate that cannot be undone. The IPCC uses radiative forcing to measure the effects of climate change, which is the difference between incoming solar radiation and outgoing infrared radiation, defined as the net irradiance at the troposphere [1]. A positive radiative forcing value is given when there is a positive net flux of energy entering the system. Radiative forcing is linearly related to the mean temperature change at the surface.

$$\Delta T_s = \lambda RF$$

Equation 2-1

where T_s is the temperature at the Earth's surface, λ is the climate sensitivity parameter and *RF* is radiative forcing.

Infrared radiation exiting the Earth's atmosphere is absorbed by Carbon Dioxide (CO_2) and other greenhouse gases, and as the concentration of these gases increases through emissions, so too does radiative forcing.

CO_2 emissions contribute most to the radiative forcing effect, along with methane and nitrous oxide, and therefore climate change action policies target CO_2 emission reductions in particular. Benchmarks are set for lumped greenhouse gas effects through the carbon dioxide equivalent (CO_2e) metric, which equates concentration levels of all greenhouse gases to the concentration of CO_2 that results in an equivalent radiative forcing effect [2]. Atmospheric CO_2 levels have been recorded at weather and climate stations globally for decades and historic levels are generally derived from geological analysis. Historic concentrations of atmospheric CO_2 from 1000–1750AD are estimated at approximately 280ppm, whilst current levels are >384ppm [3]. Combining these empirical sources, gives a picture of the growth trends in atmospheric greenhouse gases shown in **Figure 2-1** [4] and a number of studies agree that the increase in levels is likely to be a linked directly to human intervention and fossil fuel combustion [5], [6], [7].

Greenhouse gas emissions are driven by population, the economy, energy and land-use, technology and policies on climate. The most recent IPCC 5th Assessment features a statistical representation that aims to capture this type of data and use it for making projections based on these factors called the 'Representative Concentration Pathways' (RCPs) [8]. Each gas has a pathway for its future concentration and these concentrations are reflected in the radiative forcing of the scenario. The RCPs describe four different pathways of greenhouse gas emissions for the 21st century, which include a best-case mitigation scenario (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0), and a high greenhouse gas emissions scenario (RCP 8.5). The best-case scenario (RCP2.6), which is seen as very optimistic, is based on keeping global warming to below 2°C above pre-industrial temperatures. The RCPs have been developed to input into a wide range of climate model simulations to project their consequences for the climate system.

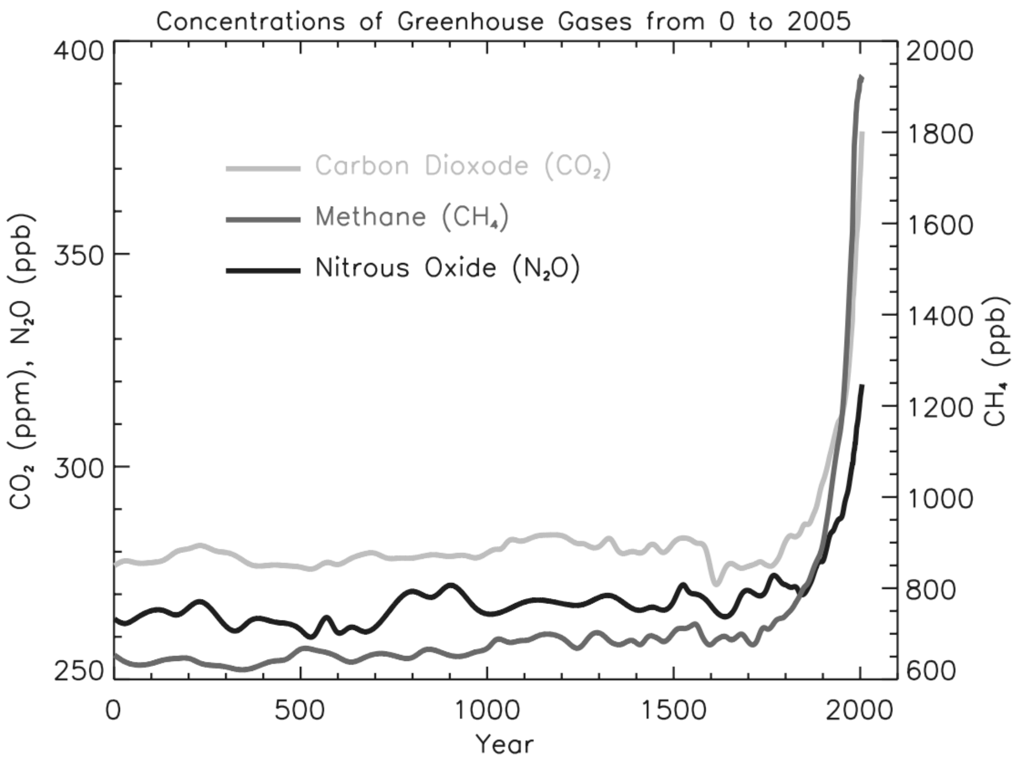

Figure 2-1: Historic concentrations of atmospheric greenhouse gases

The IPCC reports regularly on probabilistic global surface temperature rises, and its latest findings show that by 2080 we could expect an increase of between 2°C and 5°C, following various emissions scenarios (see **Figure 2-2**) [9]. The IPCC warns that a mean temperature rise of >2.5°C, relative to the pre-industrial period, could result in a range of serious global impacts, including sea level rises, increases in salinity concentrations and more frequent extreme weather events. The human impacts are wide-ranging and include risks to drinking water availability, agricultural land use and heat stress. However it is possible that even these rather dispiriting IPCC emissions scenarios border on the conservative side, since recent empirical studies have shown emission levels moving beyond IPCC forecasts [2].

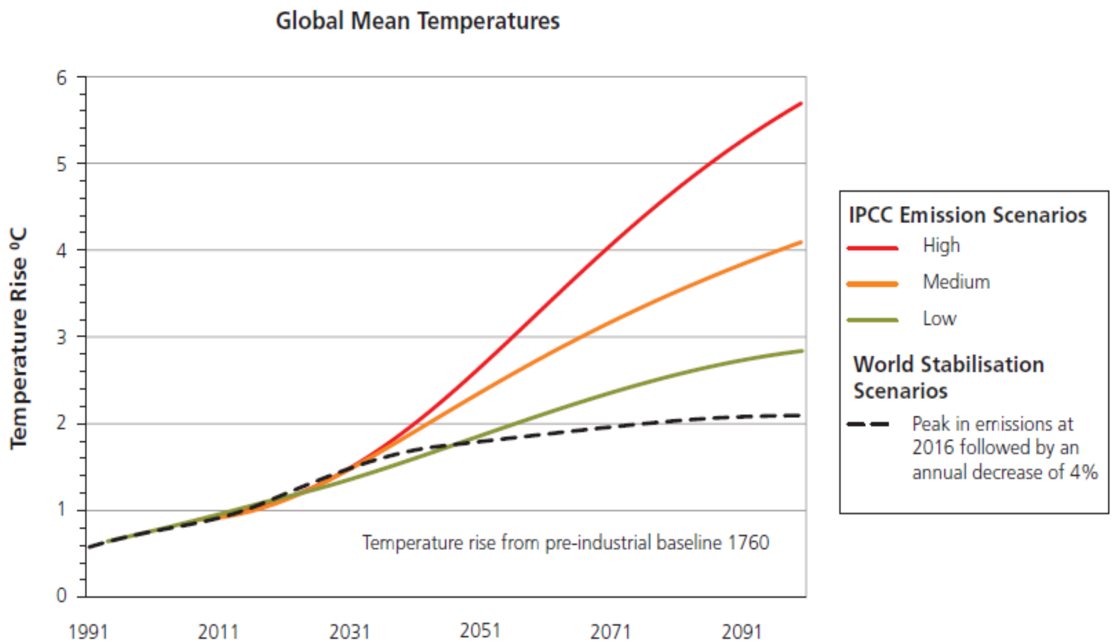

Figure 2-2: Projected global temperature rises for different emissions scenarios over the 21st century

2.1.2 Climate change in the UK

In the UK, the Climate Impacts Programme (UKCIP) published their latest projections in 2009, which show that by 2050 average air temperatures in England could increase by over 3°C and by 2080 as much as 5°C [8]. These projections were created using multiple global climate models and a high-resolution map of temperature rises plotted using the 50th percentile results [10] as shown in **Figure 2-3** [11]. These latest UKCIP projections are based on similar data and emissions scenarios to the IPCC source data, and so research work drawing on these projections can be carried out with confidence.

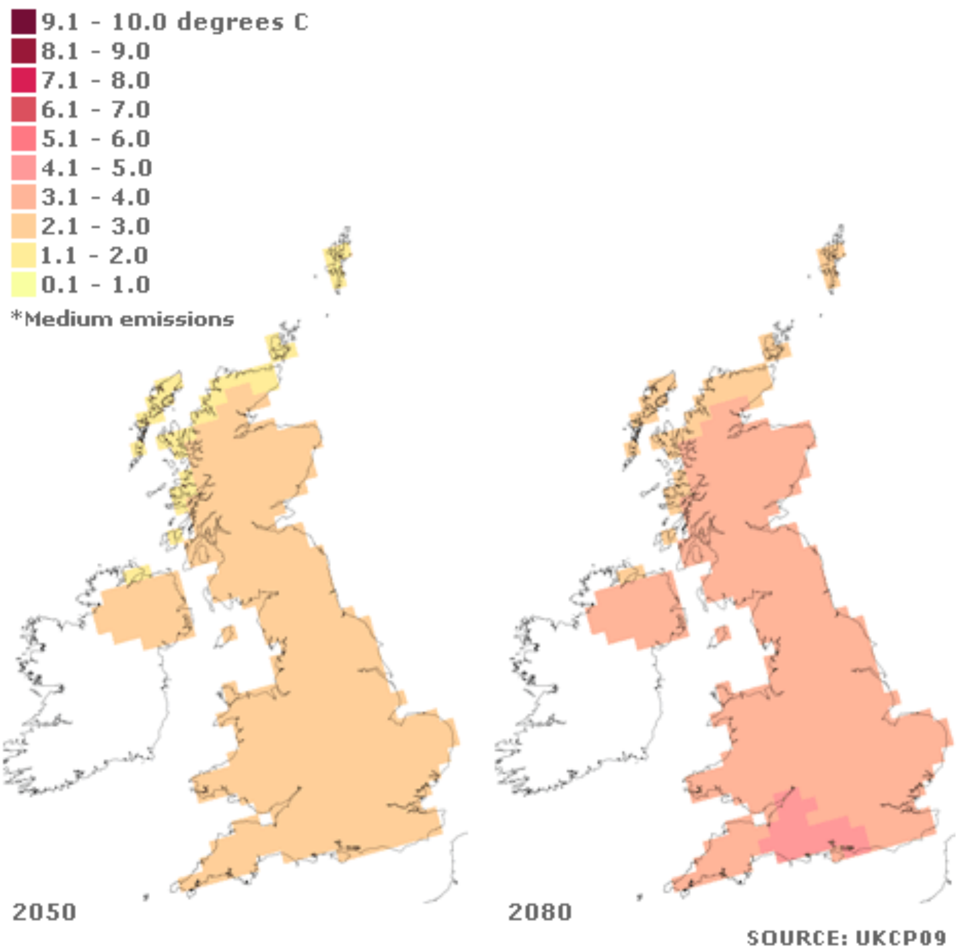

Figure 2-3: Change in summer mean temperature with 50% probability for 2050 and 2080.

2.2 Extreme weather

2.2.1 Extreme weather in climate change

Although there is much work being carried out on forecasting climate change, the prediction of extreme weather as such is far from extensive. A consequence of climate change, however, is an increase in extreme weather events such as floods, droughts, storms, cold waves and heat waves [12]. Heat waves are expected to become more intense in the future and periods of extreme hot weather equivalent to the most severe heat waves currently observed will become far more frequent in coming decades [13], [14]. A study undertaken by the Met Office suggests that extreme hot summers will be normal by the 2050s [11]. A map of projected extreme high temperature days is shown in **Figure 2-4**, with day-time air temperatures over 35°C and night-time air temperatures over 20°C [15].

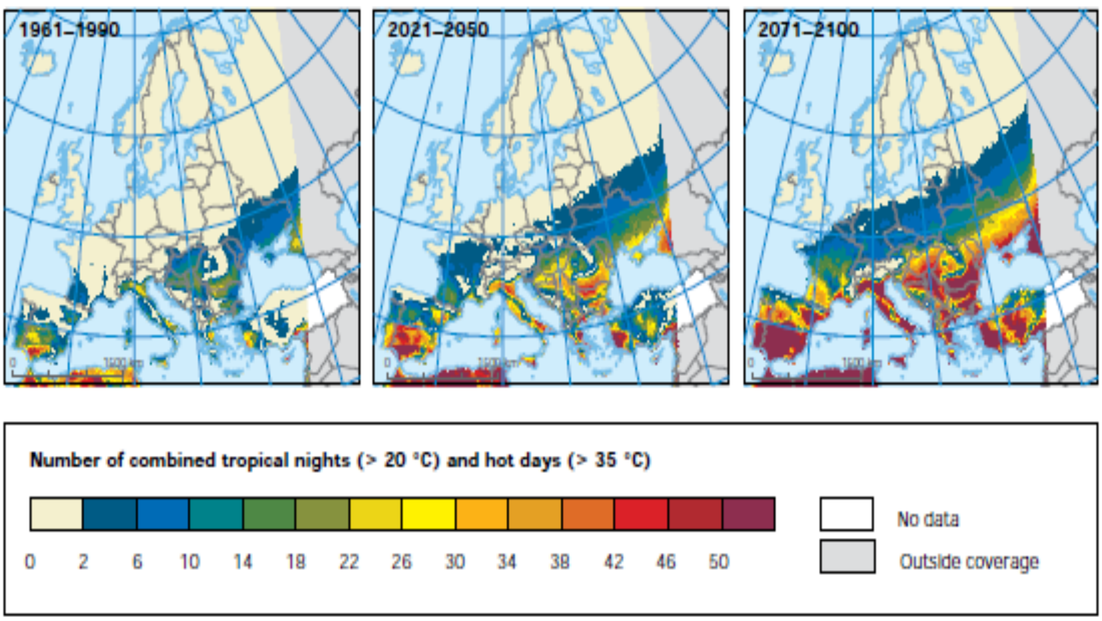

Figure 2-4: Projected extreme high temperature days and nights in Europe over the 21st century.

2.2.2 Defining heat waves

Currently heat waves are loosely characterised by meteorologists as a ‘prolonged period of unusually hot weather’, but to date a standard definition of heat waves has not been agreed [16]. Although there is no universal definition, what is common around the world is that heat wave definitions generally use air temperature alone as a metric, with either static or percentile based thresholds. These thresholds are aligned with evaluations of the local heat wave impacts on human health, which in turn are used to trigger heat wave warnings in extreme weather. Heat wave health alerts are generally issued when maximum daytime air temperature reaches a determined threshold and these thresholds vary from country to country and even within countries in order to account for human acclimatisation. In the UK for instance the Met Office advises that if there are at least 2 days of maximum daily air temperature exceeding 30˚C, and night-time temperatures exceeding 15˚C [12] (these thresholds vary slightly by region, see **Table 2-1**) then there could be a significant risk to health. Public Health England has published a heat wave plan using these threshold temperatures annually since 2004 [12].

Investigating other global heat wave definitions finds that in Brisbane, Australia, heat wave definition ‘HWD1' sets maximum air temperature thresholds at the 97.5th percentile point [17], equivalent to 33.59˚C and only slightly warmer than the London heat wave threshold of 32˚C. In Florida researchers have concluded that the heat wave threshold should be revised down to 35˚C, owing to the humid climate and the consequent apparent temperature people feel [18]. In France researchers have debated the heat wave threshold levels and concluded with '...certainty that heat-related mortality occurred at temperatures below thresholds.' [19], [20]. It is possible to set the threshold temperature at whatever level is desired, and that will be a different level depending on the target of that information, whichever level is chosen can dramatically affect the mortality forecasting outcome [21]. What can be said for buildings, which is important for this thesis, is that whilst these heat wave definitions may be applicable for outdoor conditions, they are not applicable for the indoor environment, since indoor conditions are not directly equivalent to the weather outside.

Table 2-1: Met Office heat wave warning thresholds for maximum air temperature

UK Region	Day max (°C)	Night min (°C)
North East England	28	15
Yorkshire and Humber	29	15
North West England	30	15
East Midlands	30	15
West Midlands	30	15
East of England	30	15
Wales	30	15
Southwest England	30	15
Southeast England	31	16
London	32	18

2.3 Chapter summary

This concludes the overview on climate change and future climate projections, and a look at extreme weather and heat waves. The following chapter examines thermal discomfort and human heat stress in hot conditions, and identifies new heat stress metrics for representing the equivalent temperature that the human body actually feels.

3 Hot weather and the effect on human health

3.1 Deaths in hot weather

3.1.1 Extreme weather and mortality

Extreme weather poses one of the greatest direct risks from climate change, and heat waves in particular will become a serious threat to public health in the future as the climate changes [21]. To appreciate the scale of the impact of hot weather on human health, recent studies have shown that mortality rates from heat waves in Europe already cause five times more deaths than other extreme events combined, shown in **Table 3-1** [15]. For context these figures can be compared with deaths caused by cancer, which amount to 2,660 per 10,000 deaths in Europe, and road traffic accidents which account for 140 deaths per 10,000 [22]. With the health impact from heat waves already significant, even in today's climate, this begs the question of how this risk may develop as extreme weather events increase.

Table 3-1: Number of people killed due to extreme weather events in different European regions from 1980 to 2011 per 10,000 deaths.

	Floods	Cold event	Heat wave	Storm	Wildfire
Eastern Europe	0.81	2.36	1.15	0.17	0.05
Northern Europe	0.10	0.12	0.34	0.41	0.00
Southern Europe	1.23	0.13	21.00	0.21	0.15
Western Europe	0.27	0.06	18.76	0.37	0.02

The European heat wave of 2003 is estimated to have caused over 50,000 premature deaths across Western Europe, including around some 2,000 in the UK within a hot period of just two weeks [11]. Remarkably and perhaps ominously, that heat wave occurred during a summer in which average air temperatures were just 2°C above the 1961-1990 average in the UK; it was the high daily maximum temperatures that caused the casualties. Deaths due to a cold event are to be compared to deaths caused be a heat wave, or hot event. These are direct and sudden deaths, not related to exacerbating illnesses that lead on to death some time after the event.

3.1.2 Excess deaths metric

The health impact of heat waves is often measured by excess deaths, as mortality data is readily available. Studies show that the majority of people who die in heat waves are elderly [23], [24], to the extent that impacts on age groups under 65 years are not even looked at. Those that do die in heat waves are often considered to be victims of a heat wave 'harvesting' effect, whereby impending death is accelerated during a heat wave period, dropping thereafter, and stabilising at a point in the future, as shown in **Figure 3-1**. The relative number of deaths attributed to the 2003 heat wave in France is counter-balanced by the subsequent fall in deaths thereafter (in the hatched area) [19]. This has often prompted discussion around the so-called (and arguably ill-judged term) 'heat wave harvesting effect' and whether excess deaths is a viable metric for measuring the health impact of heat waves [19].

In general though scientists agree that the metric is sound, and especially given the challenge of collecting more detailed health and disease data beyond mortality rates, excess deaths remains the most reliable way of analysing the impact of hot weather on health [25], [26].

A detailed cohort study of mortality in hot weather is not attempted in this thesis, but it is important to mention that the very young and the elderly are physiologically more vulnerable to the effects of hot weather. The issue of social isolation for older people, particularly for those that live alone, is serious during extreme weather, especially given that many periods of hot weather occur at times in the summer when families are on holiday and therefore unable to look in on older relatives, This social isolation issue was highlighted as a major contributing factor to the high number of excess deaths experienced during the European 2003 heat wave [27].

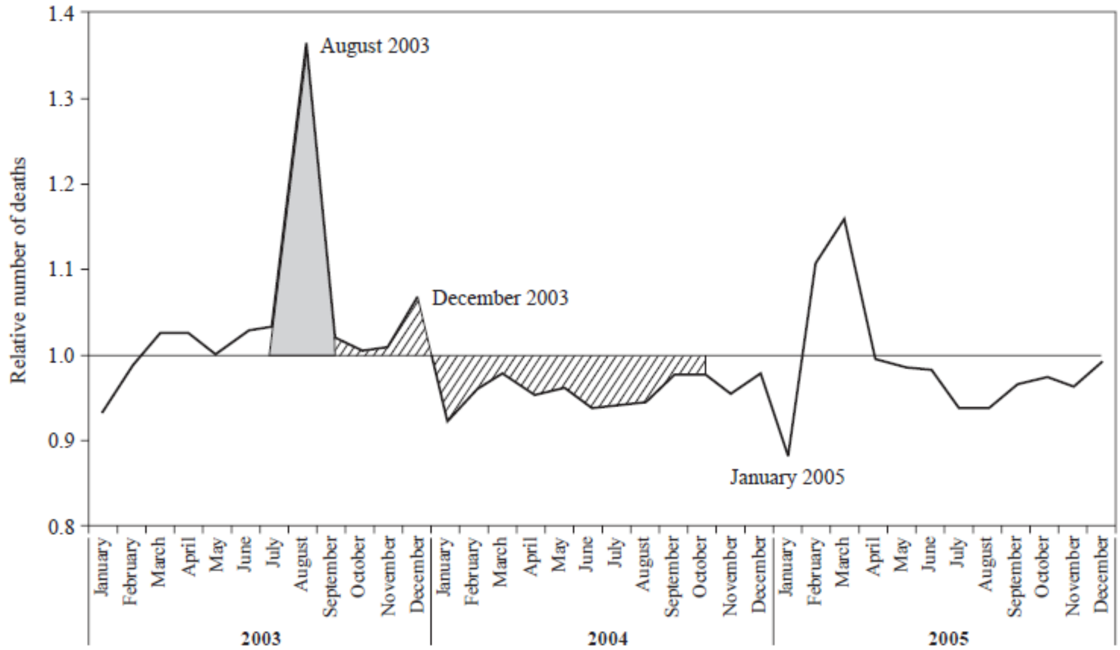

Figure 3-1: Mortality rate in France during and after the heat wave of 2003

We will now move on to discussing how hot weather conditions influence the indoor environment, and how the subsequent study of thermal comfort and the impact on health inside buildings has been treated and modelled in recent history.

3.2 Thermal comfort

3.2.1 Modelling thermal comfort

Thermal comfort has been researched for nearly 200 years, as the emphasis on human productivity during the industrial revolution led to a science of keeping workers fit and able. The environment in which people work plays a vital part in human comfort and productivity, and it was picked up quite early on that comfort depended on more than just air temperature. Chrenko's review of the historical background showed that in 1835 Michael Faraday provided evidence to the House of Commons that air temperature alone was inadequate in determining optimal thermal conditions [28], and nearly a century ago Dufton was investigating thermal conditions using heated black copper cylinders to mimic the thermal behaviour of a human body [29]. Studies of thermal radiation, air speed and thermal mass were all identified as having contributing factors to thermal comfort back in the 19th Century. The legacy of comfort for productivity, serviced by the design of the built environment has its roots in this early work, and still today, studies are carried out in the physical sciences on human performance [30]. Since then a definition has been sought to explain thermal comfort, and the ideal conditions that might satisfy it. That search has been attempted across academic disciplines, and as Nicol writes, ‘the science of thermal comfort is itself a hybrid embodying physics, physiology, behaviour, meteorology and many other disciplines’ [31].

The Chartered Institute of Building Services Engineers (CIBSE) and the architectural and structural design company Arup suggest that most people begin to feel ‘warm’ at 25°C and ‘hot’ at 28°C. Their report also defines 35°C as the internal temperature above which there is a significant danger of heat stress [32]. However, overheating is not just a function of high temperature; it is a ‘dynamic’ phenomenon and all the contributing factors and their interactions are difficult to model with steady state tools. Furthermore, some factors such as air quality may only manifest themselves in particular geographical areas, or at a more localised level, such as in the ‘heat island’ effect, which is particular to dense urban areas [33], [34].

The four main environmental parameters that affect thermal comfort are:

- air temperature
- relative humidity
- mean radiant temperature
- air velocity (or wind)

Further factors of clothing, metabolic rate and air quality are often accounted for, and some or all of these are considered when attempting to model general thermal comfort [35]. Air quality refers to pollutants, but this environmental factor will not be discussed further in this thesis.

The American Society for Heating, Refrigeration and Air-conditioning (ASHRAE) expresses comfort as ‘that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation’ [35], and the same definition is used by CIBSE in the UK [36]. Since comfort is assessed by subjective evaluation, this gives rise to discrepancies between studies. Investigations have also found that different cultures express thermal sensation with more acute language than others [37]. This obviously makes it difficult to apply a thermal comfort model globally, and so although many countries have adopted the ASHRAE definition above and its associated comfort criteria, most have also created their own comfort standards. CIBSE's comfort temperatures for naturally ventilated buildings are shown in **Table 3-2** [38]. The indoor operative temperature values shown in the table are are not considered maximum allowable values, but are used by designers in conjunction with duration criteria, such as the percentage of hours over a given temperature to assess overheating.

Table 3-2: Summer comfort temperatures in naturally ventilated buildings

Building/room type **Non air-conditioned buildings**	**Summer operative temperature** **for indoor comfort (°C)**
Home living areas	25
Home bedrooms	23
Offices	25
Schools	25

Early studies showed that a person's thermal comfort was also dependant on skin temperature. It was found that in a sedentary state, people were most comfortable when their skin registered around 34°C. However, it was subsequently found by Fanger that the preferred skin temperature was only 31°C [39]. The corollary to ASHRAE's definition of thermal comfort is that, as Fanger puts it 'people are not alike, thermally or otherwise, and it will not be possible to satisfy everyone at the same time' [39]. Fanger therefore set about creating a comfort equation, based on heat balance, and a distribution function called the Predicted Mean Vote (PMV) to describe group comfort and a Percentage of People Dissatisfied (PPD) with a thermal condition.

3.2.2 The heat balance equation

Fanger's work on thermal comfort using the principles of heat balance, was the first to gain international recognition, and has been the basis for all standards since. He theorised that there would be two conditions to satisfy in order to achieve comfort.

1. A neutral thermal sensation between skin temperature and core temperature
2. Heat production from the metabolism equals heat lost to environment from the body

As a conceptual function, Fanger expressed human heat balance in **Equation 3-1** [39]

$$H - E_d - E_{sw} - E_{re} - L = K = R + C_l$$

Equation 3-1

where

H = Internal heat production in the human body

E_d = Heat loss by water vapour diffusion through skin

E_{sw} = Heat loss by evaporation of sweat from skin surface

E_{re} = Latent respiration heat loss

L = Dry respiration heat loss

K = Heat transfer from skin to outer surface of clothing

R = Heat transfer by radiation from clothing surface

C_l = Heat transfer by convection from clothing surface

Using the empirically-derived mathematical expressions for each of the above (4 variables and 2 constants in all), and normalising the output against a 7-point voting scale shown in **Table 3-3**, Fanger was able to form a predicted distribution of group votes of thermal comfort, at any given set of room conditions.

Table 3-3: Voting scale for thermal sensation

Thermal sensation	
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

There have been other attempts to model thermal comfort, though examination of these concludes that although there are many empirical and theoretical models, Fanger's thermal comfort model relates variables applicable to thermal sensation, and is justifiably used as the primary tool in the buildings industry [36], [40].

A criticism of Fanger's work though, is that whilst it shows a very scientific approach to human heat balance, steady state laboratory results cannot accurately predict all actual votes in reality. It is more accurate to assume that people will adapt to the surrounding conditions over time by reacting in ways that will restore their comfort [31], [41]. For instance, clothing insulation is taken as a static value for the duration of a Fanger lab test, yet in reality people will adapt to higher temperatures by removing clothing layers. Other adaptations such as opening windows and turning on a fan will also be expected. In other words, 'people are not the passive recipients of the thermal environment as is often suggested by heat balance diagrams, but active participants in the interaction between the building and its inhabitants, as comfort becomes a goal which the individual will seek' [31]. In the UK especially, adaptive principles ought to be considered because most buildings are naturally ventilated rather than mechanically regulated. Moreover, using a static comfort approach, the probability of future overheating will be 5 times greater by 2020 than when using an adaptive approach [42]. To get an accurate set of predictions for future discomfort requires adaptive thermal comfort modelling together with a set of adaptive thermal standards [31], [43].

3.2.3 Indoor thermal comfort and adaptation

Fanger's comfort model is now widely used, including in Europe, USA and China, and the PMV index is as close as it comes to a set of global thermal standards [44]. The point at which a building fails to provide thermal comfort though, will naturally differ across the globe, as that will depend on the perception of occupants who have adapted to different climates. In the UK, current CIBSE guidelines describe indoor overheating as 1% of occupied hours exceeding an operative temperature of 28°C [45]. European standards in **Table 3-4** show the PMV/PPD measure used to establish good working practice. The operative temperatures are based on the PMV of a reference 50 year old man. Naturally these temperatures may result in different PMV values when occupants of different gender and age to the reference case are selected. For instance vulnerable and elderly occupants require a higher operative temperature for comfort as they are physiologically less able to adapt through sweating and less able to retain heat due to muscle and fat loss [46]. Generally the aim is to keep the percentage of people dissatisfied (PPD) at less than 10% to achieve "Class II" levels of satisfaction. In other words, 90% of people will feel thermally comfortable [47]. The class system (or category system in other documentation) is simply a level of satisfaction. So "Class II" simply refers to PPD<10% and is regarded as the highest realistically achievable PPD level [48]. The greatest issue for PMV with regards to this thesis, is that studies have shown it to be consistently unsuccessful at predicting comfort in free-running, naturally ventilated buildings [45], [49], and hence metrics using PMV could not be considered in this thesis.

Table 3-4: Example PMV/PPD temperatures for typical buildings in winter and summer [47]

Class	Thermal Comfort requirements		Operative Temperature range		Ventilation
	PPD	PMV	Winter 1.0clo/1.2met	Summer 0.5clo/1.2 met	CO_2 Above outdoor
	[%]	[/]	[°C]	[°C]	[ppm]
I	< 6	-0.2 < PMV < + 0.2	21.0-23.0	23.5-25.5	350
II	< 10	-0.5 < PMV < + 0.5	20.0-24.0	23.0-26.0	500
III	< 15	-0.7 <PMV < + 0.7	19.0-25.0	22.0-27.0	800
IV	> 15	PMV > + 0.7	< 19.0-25.0<	<22.0-27.0<	800<

An attempt to create an adaptive thermal comfort index was developed by Nicol, who argued that especially in naturally ventilated, free-running buildings, people get used to living in a changing thermal environment, and that the temperature they feel thermally comfortable at is dependent on their past experience, namely, the past air temperature of the last few days. A person's expected thermal comfort temperature can be predicted from the running-mean air temperature given by **Equation 3-2**:

$$T_{rm} = (1 - \alpha)T_{rm-1} + \alpha T_{mean-1}$$

Equation 3-2

where T_{rm} is the running mean daily average outdoor air temperature, T_{rm-1} is the running mean temperature of the previous day, T_{mean-1} is the average temperature of the previous day and α is a constant <1.

Nicol argues that the best way to establish indoor temperature thresholds is to look at the outdoor temperature. He shows in **Figure 3-2** that as running mean temperature increases, so does comfort temperature [45]. What is more, people seem to have a much greater tolerance to temperature changes in naturally ventilated buildings than buildings that are mechanically heated and cooled. This tells us either something about our changing expectations, or that our adaptability is somehow dampened when building temperature is controlled and serviced. In other words, people become less tolerant and less willing to adapt to changes in temperature if heating, ventilation and cooling (HVAC) systems do not meet our expectations. Nicol's relationship, which forms the basis for the adaptive comfort model, is shown in **Equation 3-3**:

$$T_c = 18.8 + 0.33T_{rm}$$

Equation 3-3

where T_c is comfort temperature.

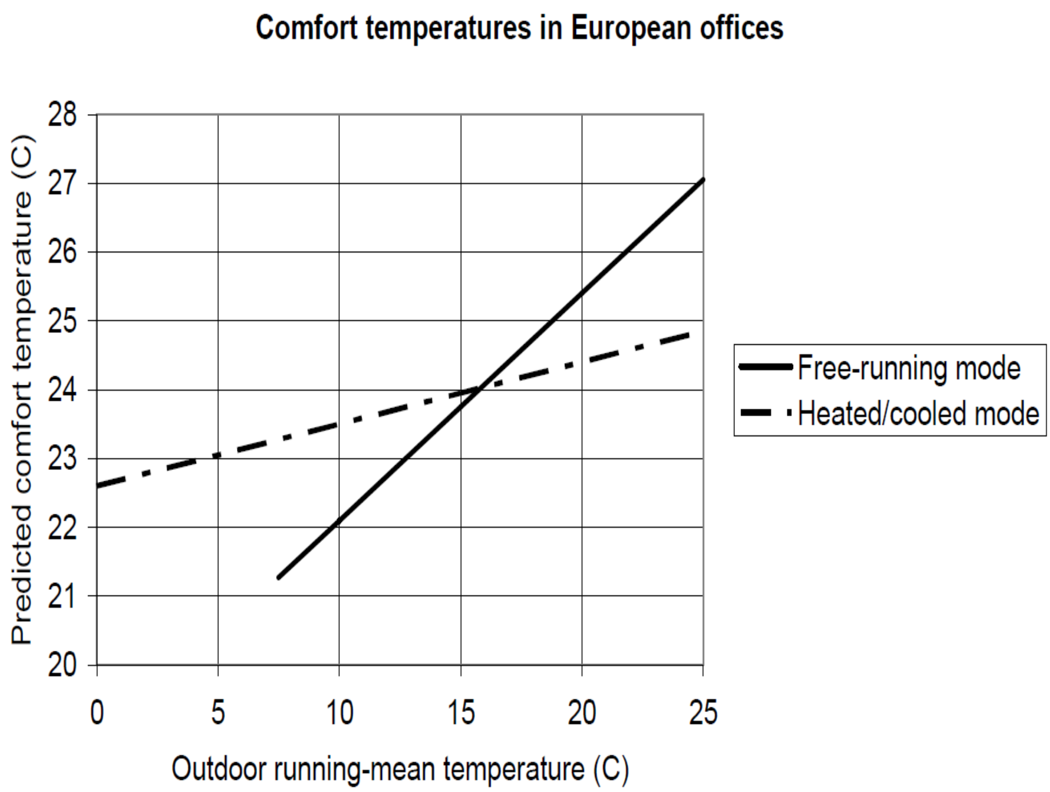

Figure 3-2: Predicted indoor comfort temperatures as a function of outdoor running-mean temperature

Heat balance, comfort temperature and adaptive comfort all try to describe conditions that satisfy human thermal comfort, yet do so from different angles. What these thermal comfort models all share in common is that they presuppose that the indoor environment does not reach thermal extremes. Such conditions may however be more frequently reached in climate change scenarios that bring about extreme weather, and so the exploration of extreme conditions within buildings and the health effects of such thermal conditions is imperative, since these scenarios will require a different model. We will therefore now turn our attention to heat stress modelling.

3.3 Heat stress

3.3.1 Heat stress metrics for extreme weather

Presently thermal comfort in near-extreme weather conditions is the primary concern for building engineers, but this thesis will also focus on human heat stress effects in extreme conditions, as this is not a factor currently taken into consideration at the design stage in building construction, and will become increasingly important to address for future climates, as hot weather extremes become normal. This requires a detailed review of heat stress metrics, created for extreme hot weather conditions. It makes sense, of course that thermal comfort models are used to test buildings, since buildings are designed not to get too hot or cold. However, given the changing climate and weather patterns, the question of what could happen to people indoors when buildings are subjected to hot weather and heat waves prompts this thesis to investigate what happens to human health in these circumstances. Heat stress modelling is usually undertaken by the military, since armed forces are often subjected to heat stresses. A physiological strain index (PSI) based on rectal temperature was developed by the US Army, given by **Equation 3-4** [50].

$$PSI = \frac{5(T_{re} - T_{re0})}{(39.5 - T_{re0})} + \frac{5(HR_t - HR_0)}{(180 - HR_0)}$$

Equation 3-4

where T_{re} is rectal temperature and HR is heart rate at different active and resting times.

This military strain index ranges from 1 to 10, with 10 giving a 'very high' physiological strain. For the purposes of this thesis, heat stress modelling needs to account for exposure to heat wave conditions and predict physiological heat stress symptoms, rather than focus on internally generated stress through heavy activity. The best known of the military strain indices to attempt a combination of environmental and physiological parameters is the heat strain index (HSI). This index is generally accepted because it combines environmental variables and body activity, though has been found to seriously under predict or over predict heat strain in several situations. The main reason is due to the number and complexity of the interactions between the determining factors.

The health impacts of overheating can include an increased risk of illness from respiratory and cardiovascular disease, and exposure to hot weather can lead to a number of heat stress disorders. The most common are shown in **Table 3-5** [51], [52]. The most dangerous health outcome is heat stroke, which is an acute condition that can lead to death and is triggered when body temperature rises above 40.5°C. Heat syncope is less severe and can lead to a feeling of sickness and fainting caused by a pooling of blood in dilated vessels in the skin. Heat exhaustion can occur after heavy perspiration, and since sweating is a primary cooling mechanism activated by a physiological response to heat, loss of salts and water from the body can lead to heat cramps and dehydration, with body temperature reaching 37.5-38.5°C. Heat oedema which mainly takes the form of swollen ankles is another minor illness, as are heat rashes [36]. For the more minor heat related illnesses, drinking water and replenishing the body’s salt levels often suffices for a return to full health. However, if internal body temperature keeps rising, eventually the body's capability to sweat ceases as fluid levels become too low. When the internal body temperature passes the 40°C mark, confusion, disorientation and convulsions occur, resulting in organ failure, brain damage and death.

Table 3-5: Causes and symptoms of human heat stress

Condition	Cause	Symptoms
Heat stroke (Risk of fatality)	Body temperature rising above 40.5°C	Mental confusion Mottled or cyanotic skin Loss of consciousness Convulsions
Heat syncope (Risk of illness)	Pooling of blood in dilated vessels of the skin / lower extremities	Temporary loss of consciousness
Heat exhaustion (Risk of minor illness)	Loss of salt or water after heavy perspiration for several hours	Cramps Skin eruptions

All of the above conditions could constitute a danger to our health, and the impact on health services and the loss in productivity would be greatly felt. Heat stress, especially in future hot weather needs to be investigated to assess the scale of this impact. For a full heat stress impact flow path see **Figure 3-3** [51].

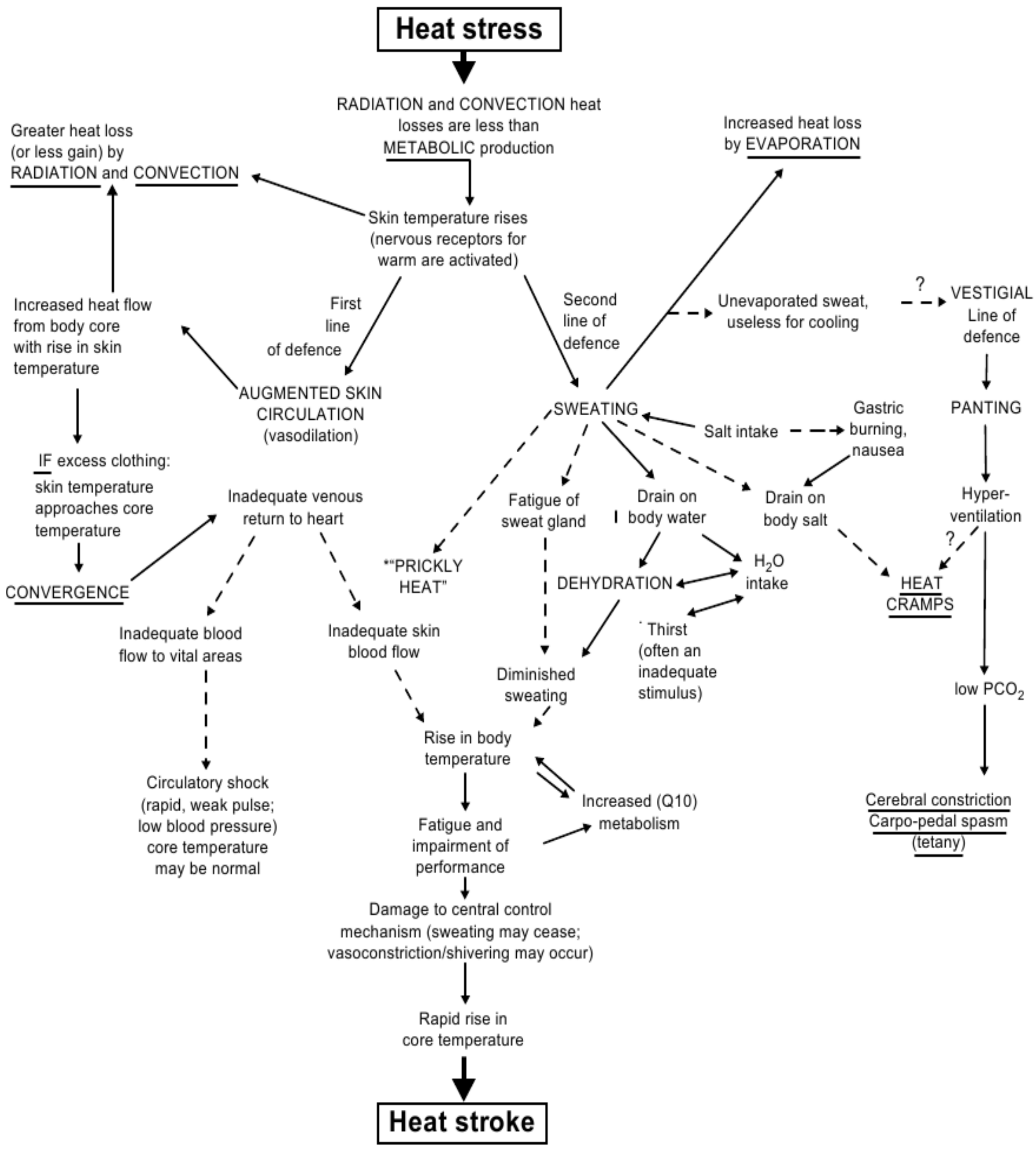

Figure 3-3: Flow path of illnesses from heat stress

3.3.2 The Apparent Temperature (TAPP)

One attempt to define exposure to heat waves considers both extreme daytime and high night-time temperatures. The apparent temperature (TAPP) scale is a discomfort index based on air temperature and dew point temperature, as shown in **Equation 3-5** [53].

$$T_{app} = -2.653 + 0.994\ (T_{air}) + 0.0153\ (T_{dewpt})^2$$

Equation 3-5

where T_{app} is the apparent temperature (or the sensation temperature), T_{air} is air temperature and T_{dewpt} is the dew point temperature (to introduce a humidity factor).

Using this scale, a heat wave is defined as a

1) period of at least two days with maximum TAPP temperatures exceeding 90% of the monthly distribution or a

2) period of at least two days in which T_{min} exceeds 90% and maximum Tapp > median monthly value

3.3.3 The Universal Thermal Climate Index (UTCI)

Whilst the TAPP index incorporates air temperature and humidity, the Universal Thermal Climate Index (UTCI) is an index which lumps together all meteorological variables that affect the human heat balance equation [54], as set out by Fanger [39], [44]. In theory TAPP and UTCI could better identify health risks in hot weather, since they account for a multitude of variables that affect human heat stress. In the case of UTCI, an equivalent temperature is calculated with associated health risks (**Table 3-6**). With reference to **Figure 3-3**, it is important to clarify that any multi-parameter indices such as TAPP or UTCI will be limited in their ability to handle dynamic situations. For example the frequency with which air speed (for example) will change in value compared with the frequency with which air temperature or humidity values will change over a given time period will itself vary. It is therefore only sensible to take instantaneous values for each parameter to calculate the TAPP or UTCI value for that moment in time. With regards to use in building thermal modelling, time-averaged values for one hour periods will be taken, which has been validated in other works [55]. Use of the UTCI for outdoors is validated in its original operational procedure [54], [56], whilst its use for indoor thermal comfort has also been validated by the UTCI-Fiala model [57] and in domestic buildings [58].

Table 3-6: The UTCI temperature scale and equivalent heat stress on a human body

UTCI (˚C)	Stress Category
>46	extreme heat stress
+32 → +46	very strong heat stress
+26 → +32	strong heat stress
+13 → +26	moderate heat stress

+9 → +13	no thermal stress
0 → +9	slight cold stress
-13 → 0	moderate cold stress
-27 → -13	strong cold stress
-40 → -27	very strong cold stress
-46<	extreme cold stress

The UTCI combines wind speed, radiation, humidity and air temperature, and is defined as the air temperature of the indoor reference environment, which would produce an equivalent dynamic physiological response. The UTCI was developed from testing an advanced multi-node human thermoregulatory model [59] in simulated reference weather conditions, generating equivalent body temperatures. A polynomial regression model was applied to the body temperature outputs in order to generate a numerical equation for use in computational code. The UTCI function can be simply described in **Equation 3-6** [56] whilst detailed background on the original development can be found on a dedicated UTCI webpage [60].

$$UTCI(Ta, Tr, va, pa) = Ta + Offset(Ta, Tr, va, pa)$$

Equation 3-6

where *Ta* is air temperature, *Tr* is mean radiant temperature, *va* is air velocity and *pa* is vapour pressure. The offset to *Ta* is found by comparing the actual model response to the human physiological response under reference conditions.

Studies have shown that the UTCI is potentially more suitable than air temperature for measuring the impact of weather on health [61], [62]. The UTCI is based on the human physiological response to environmental variables and the heat stress that a human body feels, which is a complex combination of air temperature, humidity, solar radiation and airflow [50].

3.4 Chapter summary

In this chapter an overview is given on the development of comfort models and the differences between these and heat stress models. It has been established that for extreme environmental scenarios it is necessary to focus on heat stress effects, and the UTCI has been identified as an appropriate index for human health. A table detailing the advantages and disadvantages of each index is presented below.

Table 3-7: Comparisons of comfort and heat stress metrics

Metric	Advantages	Disadvantages
TA (Air temperature)	Currently used by most weather and public health organisations for heat wave alerts (including the UK Met Office).	Does not account for other weather variables that affect human heat stress (it does not account for humidity or radiative temperature).
TAPP (Apparent Temperature Percentile Index)	Accounts for air temperature and humidity and has previously been used in analyses of heat waves health impacts.	Does not account for all weather variables that affect human heat stress (it does not account for radiative temperature).
UTCI (Universal Thermal Climate Index)	Accounts for all weather variables that affect human heat stress.	Not particularly dynamic as index merges frequently varying parameters such as

		wind speed and relatively steady state variables such as humidity.
PMV (Predicted Mean Vote)	Physiological-based index that includes most parameters relating to human comfort.	Broadly unsuccessful at predicting thermal comfort in naturally ventilated buildings
PSI (Physiological Strain Index)	Used by the military for heat stress assessment	Based on self-induced internal temperature through heart rate activity, rather than on weather variables.
HSI (Heat Stress Index)	Used by the military for heat stress assessment	Can seriously under predict or over predict heat strain in several situations, due to the number and complexity of the interactions between the determining factors.

In the next chapter the background of building modelling, design and regulations around thermal conditions are explored, and peak thresholds for the indoor environment will be established, seeking the most appropriate metric for predicting significant excess deaths in hot weather. This will be achieved by using various metrics, including the UTCI, to analyse current hot days and heat waves alongside mortality rates.

4 Establishing peak thresholds for buildings

4.1 Building regulation and modelling

4.1.1 Building regulations

Given the high proportion of time people spend indoors in developed countries; a reduction in overall building energy use is an area of focus in many countries to avoid increasing carbon emissions [63]. The built environment accounts for a significant proportion of all carbon emissions globally, and in the construction phase alone, the cement industry is estimated to be responsible for 5% of anthropogenic carbon release [64], whilst habitation of buildings pulls greatly on global energy consumption. In Europe the Energy Performance of Buildings organisation (EPBD) is responsible for targets relating to energy consumption in the built environment, and energy use certification. European targets for energy use are a reduction of 9% from a 2008 baseline over a 10-year period [65], whilst minimum energy performance requirements form part of UK building regulations [66], [67]. All new non-domestic buildings should be zero-carbon by the end of the decade [68]. The building energy reduction target is clearly an integral part of the pledge to reduce emissions, and at the same time albeit a beneficial consequence rather than a regulation, energy use reduction should aid better indoor thermal comfort. For domestic dwellings the Standard Assessment Procedure (SAP) is used for energy performance assessment in the UK. SAP is a methodology for calculating energy use, associated running costs and CO_2 emissions. The overheating test, which is detailed in the SAP documentation and applicable to the summer months of June, July and

August, gives a likelihood rating of high internal temperatures during hot weather. It is not integral to the regulations and does not affect the calculated SAP rating or CO_2 emissions, and so should be treated as a guide only. The overheating calculation is related to factors that contribute to internal temperature, such as solar gain (orientation, shading and glazing transmission); ventilation (window opening), thermal capacity and mean summer temperature for the location of the dwelling. [69] The climatic data used in SAP is taken from current regional averages, and as such, overheating tests will be relevant to today's climate only.

4.1.2 Building modelling and thermal simulation

To maintain a comfortable environment and to minimise energy use, architects and engineers model buildings in the pre-construction phase to test thermal performance. The first building models prior to computers were generated by hand and were reliant on curve response data for their prediction of energy and thermal outputs. When computational building models were developed, dynamic modelling of multi-zone spaces and discrete time-stepping analysis became possible [70]. Steady state models are able to perform energy calculations over long time periods and where thermal equilibrium is achieved. Dynamic thermal models deal with transient energy calculations and can be used for building analysis over short time periods, but require detailed data input, such as detailed geometry and real site weather data, and simulating at hourly intervals. That is not to say that data inputs will be fully accurate, as there is naturally a great deal of uncertainty real buildings. Indeed, accurate data inputs rely on sufficient monitoring, an understanding of the building's thermal performance post construction and clever modelling of inhabitant behaviour; accuracy of the latter being the most difficult to achieve. Presently dynamic thermal models are rarely used outside the non-domestic building sector, but there are calls for this to change to include the domestic sector, given the prospect of significant future warming [71].

Current regulations for overheating focus on whether the temperature in a whole building is likely to exceed a certain threshold [72], which is either a static maximum temperature value, or an adaptive one used in naturally ventilated, free-running buildings where human thermal comfort conditions are more tolerant. Building engineers often use software packages such as *IES, ESP-r, TAS, EnergyPlus* and *DesignBuilder (*based on *EnergyPlus)* to model buildings at the design stage, using thermal comfort models and external air temperature to test thermal performance [73]–[75]. Values for a range of parameters such as building geometry, weather, internal gains and number of occupants are input. Some values can be dynamically varied during a thermal performance simulation (such as number of occupants), and a projected PMV/PPD value, based on Fanger's model, is calculated. Software packages are generally able to calculate air temperatures for any given building model for all hours over a yearly simulation. If the temperature is too high, or the temperature exceeds a certain threshold for too many hours, the building will fail an overheating test. The procedure does not consider any adaptations; which occupants will make to attain thermal comfort. The advantages of this approach are in its low computational cost and relatively simple modelling setup, and as a consequence can readily and swiftly produce simulations for building designers, and for many situations this method will give good results, with the final output a measure of human response (see **Table 3-3**), but the question is whether this is the correct approach, or whether a finer method is needed.

4.2 Overheating in buildings

4.2.1 Thermal transmittance and heat capacity

Like all objects, a building is governed by thermodynamic processes. Heat balance, or equilibrium point, is naturally never achieved, since the external conditions surrounding the building envelope are ever-changing. A building will heat up and cool down regularly and this dynamic heat exchange can be analysed by looking at thermal transmittance and capacitance. There are several ways in which heat can enter a building and several factors of the building design that enable a building to store heat or dispel it. Thermal transmittance between the building and the external environment is governed by a number of processes and drivers. Solar exposure of the building's envelope, the effective solar heat gain to the building, the rate of conductive and convective heat gain from ambient air and natural ventilation and passive cooling of the building are the forms of heat exchange between the building and its environment.

Conduction will occur when there is a temperature gradient between the outside and the inside through the building envelope, which comprises its walls, floors, roofs, doors and windows, and so building material, wall thickness, ground and wall thermal capacitance and material resistance are all factors of a building that are affected by heat conduction, and hence need to be considered at the engineering design stage. Radiative heat transfer (both direct and indirect) occurs primarily due to solar radiative effects. Direct radiation will occur through glazed areas such as windows, whilst indirect radiative heat will cause transmittance of energy to the walls and structure. Solar radiative temperatures can typically be upwards of 50°C in summer, and so can have a large effect on the addition of heat to the building. Convection of air will either heat or cool a building, depending on the temperature difference between the air outside and the air inside; this process of heat exchange will occur through ventilation, through windows, mechanical ventilation and permeability of the building fabric. Internal gains from any energetic objects, such as occupants, appliances and services (heating, plumbing and electric installations) will increase the internal energy of the building and therefore increase heat. In addition to thermal transmittance, the heat capacity of the building fabric; its thermal mass, will have an effect on the temperature of the internal environment. Energy stored in the building material will cause heat to flow into the indoor space when there is a temperature gradient (typically at night when the air is cooler).

Key design considerations for both convection and solar radiation gains, other than the building shape and material, include the percentage of glazing in the building and the orientation of the building, relative to the sun path. All these external thermal gains are driven by weather, and weather parameters represent the input conditions into any building physics modelling, and are illustrated in **Figure 4-1**, **Figure 4-2** and **Figure 4-3** [76].

Building designers need to consider both internal and external heating sources. External gains, such as solar radiation, will change the localised thermal environment around a window for instance, whereas internal gains, such as electronic equipment may be scattered about the building, and will be harder to model. In the pursuit of thermal comfort, internal gains need to be controlled, since a simple solar shade can limit radiant heat from outside, yet unwanted internal heat gains need to be actively expelled. As all electrical energy ultimately ends up as heat through processes of radiation and convection, it is important to assess the impact on the space heating and cooling demands [77].

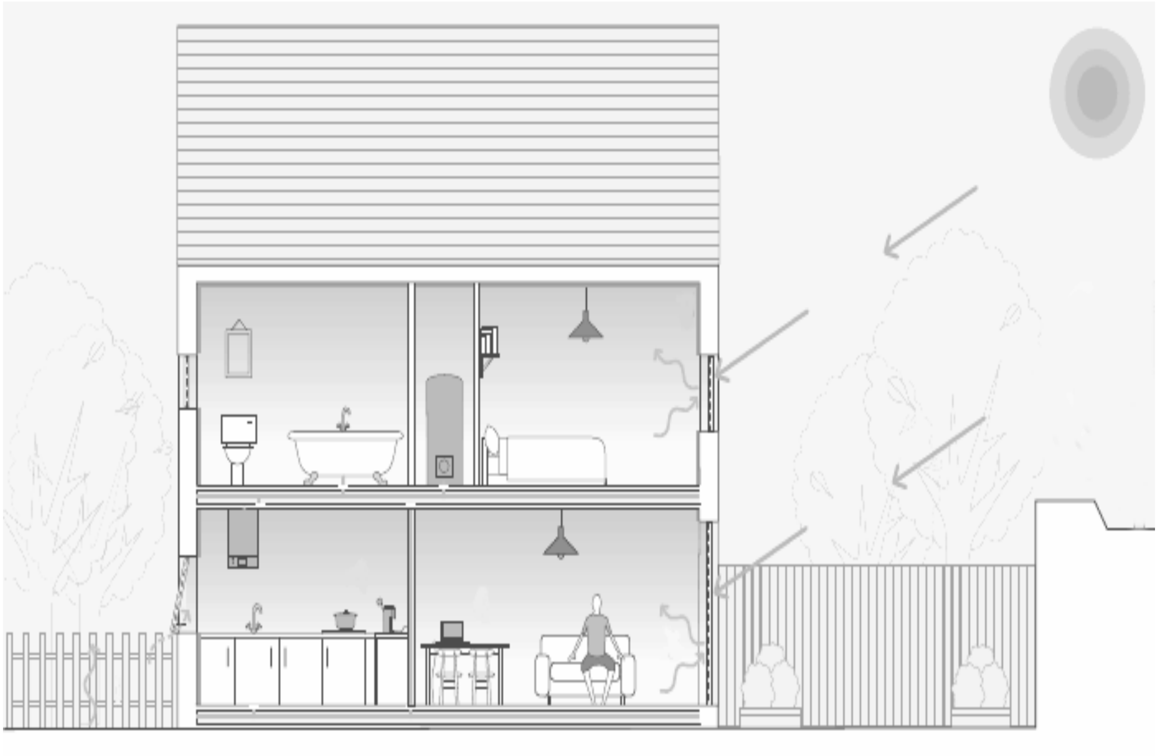

Figure 4-1: Illustration of solar radiative heat transfer and internal gains causing internal heating

Figure 4-2: An example sun path, and consequent solar heat gains at the building surfaces, illustrating the need to factor building orientation into designs

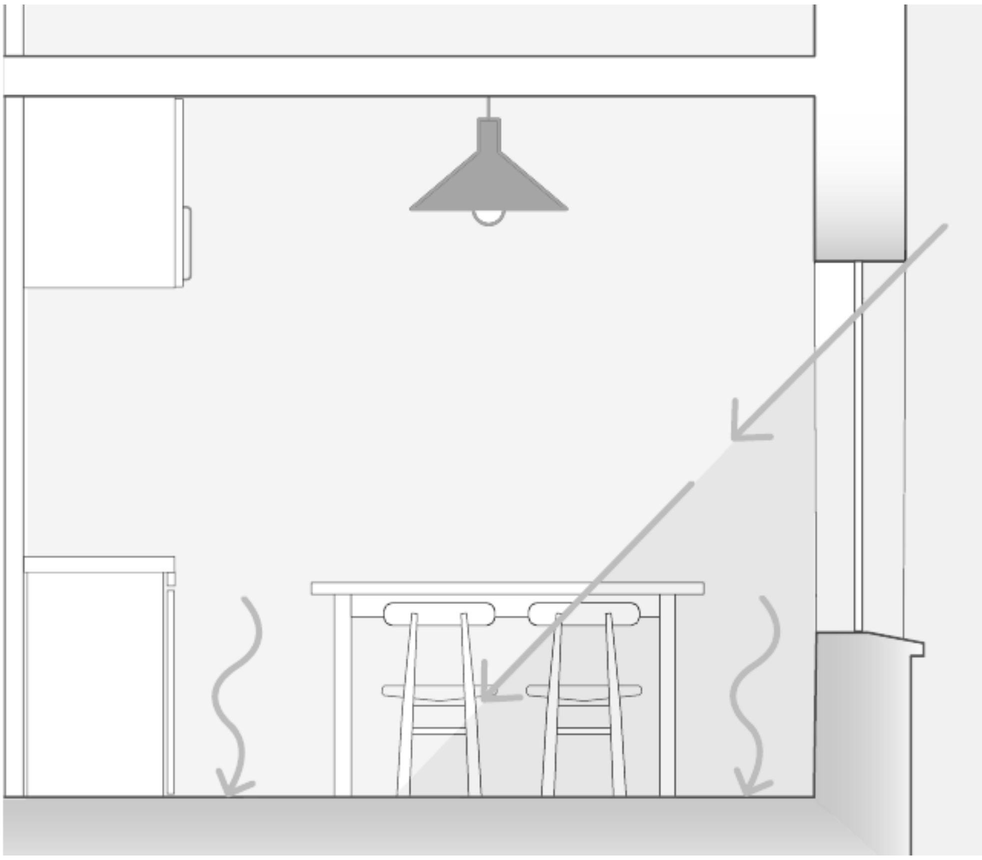

Figure 4-3: Illustration of direct solar radiative heat transfer through glazing onto internal building surfaces.

4.2.2 Thermal performance and overheating

Homes in the UK are becoming increasingly well insulated and impermeable, and current building design practices are geared towards keeping people warm in winter, through the retention of warm air and the capturing of radiant solar heat [78]. The current recommended winter operative temperatures for homes and offices are shown in **Table 4-1**.

Table 4-1: Indoor operative temperatures for buildings in winter

Building/room type	Winter operative temp °C

Homes

Bathrooms	20-22
Bedrooms	17-19
Kitchen	17-19
Living Rooms	22-23
Offices	
Conference Room	22-23
Computer Room	19-21
Office Space	21-23
Open Plan Office	21-23

As a result of ambitions to design out the need for heating in homes, many local planning authorities make the use of low carbon technologies a specific planning requirement to achieve reductions in carbon emissions, and the following factors are considered as part of standard building design [68]:

- Best orientation to optimise the impact of solar gain
- Optimisation of glazing
- Maximum air tightness to reduce infiltration
- High insulation levels
- Appropriate use of thermal mass

The drivers for change to design low carbon buildings are fully understandable given the current UK climate, and for the most part these low carbon technologies enable year-round thermal comfort. Guidelines prioritise better winter efficiency and most buildings have heating systems installed, whilst very few domestic homes have mechanical ventilation and cooling systems. With a warming climate typical winter heating periods are likely to decrease, since in the future it is unlikely people will need to heat their homes as much, but the need to cool them in summer will increase, and there will come a point when the cost to cool buildings mechanically in summer will be greater than heating them in winter. Studies have shown that global energy demand for energy use in heating and air conditioning should reach parity by around 2070, and that thereafter, energy use for air conditioning increases as heating demand decreases (see **Figure 4-4**) [79].

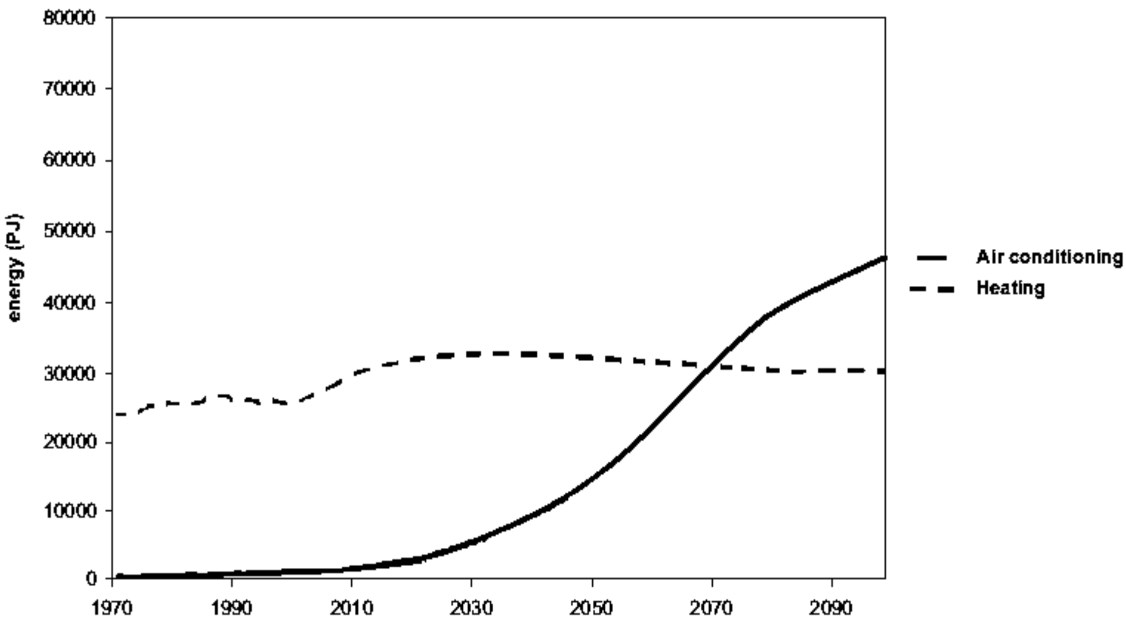

Figure 4-4: Predicted global energy demand for heating and for air conditioning in 21st Century

For the built environment, a key concern for the UK government identified in the 2008 Stern Review, is that a likely response to hotter summers will be the installation of air-conditioning, as has been seen in the USA, Australia and southern Europe [80], which will severely hamper the UK's efforts to reduce its greenhouse gas emissions to nearly zero by 2050 for all buildings [81]. It is up to architects and building engineers to design low carbon retro-fit solutions and new building stock that will cope with the effects of future hot weather, without deploying air conditioning as the default solution, and thereby compounding the problem of increasing carbon emissions, climate change and overheating [82], such that during extreme hot weather and heat wave conditions the internal environment can become unbearable [83], [61]. The greatest impact of overheating will be felt by the existing stock of free-running, naturally ventilated buildings without the means to provide mechanical cooling [45], and so a focus of this thesis is on the impact of climate change in free-running buildings, where people spend most time [84].

Overheating is a particular problem in modern flats and apartments, since the average one-bedroom home is less than 50m^2 and is unlikely to be double aspect, since there is no legislation to ensure cross-ventilation [85], resulting in city apartment block developments that only have one room orientation, without cross-ventilation. Some retro-fit solutions exist such as passive cooling methods using blinds and external shading. These measures could help people avoid the reliance on air-conditioning and increased energy consumption [11], whilst other solutions include increasing mixed-mode building stock [86], which not only result in a greater tolerance of thermal comfort temperature, but also consume far less energy. When inhabitants are given choice as to how they can adapt indoors, for instance by opening windows, they are shown to be more tolerant of greater deviations from the comfort temperature, or in other words they are less dissatisfied than inhabitants of controlled environments [49]. Whilst retro-fit solutions will be essential in adapting buildings, the fundamental design principles at the pre-construction stage really should account for hot weather conditions to avoid overheating pitfalls [87].

The consequences of overheating can affect people greatly and there are recorded instances where serious health issues caused by overheating have led to legal action [76]. To prevent a building from overheating, it is first important to define the term ‘overheating’, which is generally understood to be the ‘accumulation of warmth within a building to an extent where it causes discomfort to the occupants’ [44]. It is important not to assume that this will occur solely as a result of high air temperatures. There are other factors that will add to the feeling of warmth, such as relative humidity and solar gain, as we have seen. There is no statutory maximum internal temperature in UK Building Regulations or current health and safety guidance, beyond the SAP overheating checks for domestic buildings [31]. Whether there should be or not is debatable; clearly there is an argument to say that since the majority of domestic buildings are existing stock, it would be terribly complicated and contradictory to impose thermal maxima on any works that require building regulations approval, given the current importance placed on keeping old and leaky homes warm. However, given the findings from this thesis, it would certainly be prudent for regulations for upper thermal limits to be in place for new domestic buildings, as it is arguably just a case of adding another parameter to a set of design criteria; one which could potentially avoid future health problems to inhabitants due to overheating.

The challenge is to derive appropriate overheating criteria for the UK that define when a building is too hot for comfort [45]. At present, the CIBSE procedure for testing overheating in certain types of buildings is to assess the number of hours when the building will be above the discomfort threshold temperature of 28°C [45]. If the indoor temperature exceeds 28°C for more than 1% of the occupied time, then the building is said to have failed to provide thermal comfort. Building regulations in this area are designed to keep people safe and protect against thermal discomfort, and there is some practical guidance published for dealing with building overheating [88]. For instance Building Bulletin 101 (Bb101) issues guidance that for schools there should be no more than 120 hours when the air temperature in the classroom rises above 28°C, that internal air temperature should not exceed 32°C, and that internal to external temperature difference should not exceed 5°C [89], whilst subsequent publications have also incorporated adaptive comfort standards [31], [42], [90].

4.3 Reference weather years in the UK

4.3.1 The test reference weather year (TRY)

Thermal performance is judged primarily on whether buildings can keep their occupants comfortable, providing shelter from the extremes of the outdoors and maintaining a comfortable indoor thermal climate [81], and so at the design stage buildings are generally simulated to cope with a typical climate, represented by an hourly weather data series [91]. The data needed to run these simulations must also be site-specific to take into account the regional climate. In order to simulate building performance, architects require scientists to develop simple reference weather sets to use as input conditions, since the vast amount of data collected by weather stations is both overwhelming and costly to purchase. Currently these data sets are derived from observations gathered from local weather stations around the UK, and are referred to as reference years. In the UK the standard is the Test Reference Year (TRY), and is created by piecing together the calendar months that have exhibited the closest dry bulb air temperatures, wind speed and solar radiation to an average value, typically over a 23 year period (1983–2005). The TRY aims to give a good 'average' calendar year whilst reducing the amount of computing simulation time by a factor of 20 [91]. An example of the years selected for the Heathrow TRY is shown in **Table 4-2**.

Table 4-2: Months and years selected to make the months in the Heathrow TRY

Month	Year Selected
January	1988
February	2004
March	2004
April	1992
May	2000
June	2001

July	1991
August	1996
September	1987
October	1988
November	1992
December	2003

4.3.2 The design summer weather year (DSY)

Whilst the TRY is a good reference on which to base average climate conditions, it will fail to describe conditions that would bring about overheating, and so to test for that, a new reference year was created: the Design Summer Year (DSY). Drawing from the same 23 year baseline period of weather records as the TRY, the DSY is created by selecting the third warmest summer (April to September), with the aim of creating a reference data set that, when applied in building simulation software, will test for building overheating during hot summers. Globally, testing for overheating is often performed using a threshold air temperature [92], though some countries such as Germany and Denmark also use reference weather years as in the UK [93], [94].

4.3.3 Issues with the DSY methodology

Unfortunately the DSY methodology encounters several difficulties [95]; first, in some regions of the UK the DSYs have been found to produce less overheating than the TRYs, that are used to test building energy use in normal weather conditions [91]. Second, overheating assessments rarely account for extreme weather such as heat waves, as current DSYs are only designed to represent 'unusually warm' weather. Third, the tests are based on air temperature alone, ignoring several other weather variables that affect the thermal impact on the human body [96]. Fourth, morphed DSYs that are currently supplied by CIBSE for future scenarios may not contain warm events, since they are based on historic weather that does not necessarily contain warm events.

Perhaps the most surprising flaw in the current DSY methodology is that there is no guarantee of any hot events, which means that periods of hot weather that can cause people heat stress in buildings is entirely possible within the current DSY reference years. From the Met Office definition, a heat wave can last two days or more, and so given the DSY is formed from a whole summer, a heat wave occurring in an otherwise cooler period risks being overlooked. In fact there are some locations with TRYs that contain more hours of hot weather than their respective DSYs, as shown in **Table 4-3** [95], where the thermal performance for an office with glazing on all walls was tested for UK locations using both the TRY and DSY. Instances where the building simulation results found the TRY overheating hours to be greater than DSY overheating hours are underlined in bold, and clearly there are a number of locations where this is the case; critically this is how overheating in certain buildings is tested in the UK. DEFRA's report finds that as average temperatures increase, so too do the number of hot days, and this relationship is not necessarily linear [11]. It is therefore important to investigate the types of events which cause overheating in buildings and to introduce redeveloped reference data, suitable for heat stress testing [97].

Table 4-3: Comparison of the number of hours above 25°C and 28°C in the 14 TRY/DSY files. (Data pairs where DSY hrs < TRY hrs are shown in bold underlined)

Weather Station	**Hours > 25°C**		**Hours > 28°C**	
	TRY	**DSY**	**TRY**	**DSY**
Belfast	0	8	0	0
Birmingham	71	109	14	27
Cardiff	13	18	0	0
Edinburgh	6	10	0	0
Glasgow	0	11	0	0
Leeds	51	178	2	58
London Heathrow	106	267	28	63
Manchester	**<u>56</u>**	**<u>52</u>**	8	14
Newcastle	**<u>18</u>**	**<u>6</u>**	**<u>1</u>**	**<u>0</u>**
Norwich	**<u>56</u>**	**<u>35</u>**	**<u>8</u>**	**<u>1</u>**
Nottingham	**<u>50</u>**	**<u>25</u>**	0	3
Plymouth	3	36	0	9
Southampton	**<u>46</u>**	**<u>26</u>**	**<u>7</u>**	**<u>0</u>**
Swindon	49	66	4	4

4.3.4 Using reference weather data for overheating testing

Since the DSY is currently the only reference weather data used to test overheating in buildings, and since there are a number of significant flaws in this reference data that have not yet been adequately addressed, the result is that buildings are being constructed and passing thermal performance assessments using potentially unsuitable standards. In other words, there is no telling whether newly constructed buildings will overheat or not. Buildings constructed today are expected to have a life span of around 100 years [98]–[100], and as the climate changes, extreme weather will challenge buildings to perform under conditions they are not currently designed for, though they may be retrofitted to cope with changing conditions. Recently, probabilistic DSYs have been created for London to try and correct some of these issues [101]. These new DSY reference years are all based on air temperature as a singular metric, and so one of the central aims of this thesis is to extend the new DSY methodology to create reference years that are based on more weather parameters, tuned with a new temperature metric for health inside buildings, and to do so for both current and future climates.

4.4 Developing peak threshold metrics for thermal performance

Building designers need to know the impact of extreme events on the internal conditions inside buildings, because one of their primary focuses is to keep people thermally comfortable at all times and sheltered from the weather outside, filtering the external conditions to attain indoor comfort. This thermal comfort function of buildings generally works well in most conditions, but can lead to difficulties in extreme weather. In extreme hot weather the human physiological response can quickly turn from a minor illness to morbidity and even death [102] [103]. In such weather, buildings should at the very least avoid amplifying the external conditions, but ideally should retain an environment that is thermally comfortable.

How a building filters external conditions and how the consequent indoor environment is reached is dependent on its construction and design, however there are countless different buildings types, and thermal performance testing at the design stage must be done on a case by case basis. Buildings cannot uniformly be tested for thermal impact on inhabitants, so a solution would be to seek an index and an accompanying metric that captures mortality for many types of buildings. With current overheating in buildings policy reliant on external air temperature alone and adaptive comfort modelling, it would be prudent to consider the efficacy of indices for the internal environment that can lump together weather parameters that affect human health for an equivalent indoor temperature, thereby giving a potentially more realistic temperature felt by people indoors [104].

The greatest discomfort is found when temperatures increase rapidly from the recent average, and whilst adaptive comfort measures are aimed at replacing overheating metrics such as the number of hours over a fixed threshold, they generally do not address the question of maximum temperature within buildings and what that threshold should be to safeguard human health.

CIBSE's TM52 provides a maximum acceptable temperature that is related to the comfort temperature, but this is not an indicative temperature at which health deterioration occurs. Armstrong finds that across English regions excess deaths occur at around the 93rd percentile of maximum daily air temperature and suggests that health risks should be monitored using percentile based temperature thresholds for that particular region [105]. When this is compared to the Met Office heat wave static air temperature thresholds, which sit at around the 99.9th percentile for the majority of regions, it is likely that excess deaths will occur before health warnings are issued, and that current external air temperature thresholds are unsuitable. Percentile based thresholds are not uncommon internationally, as has been established in the case of the Australian 'HWD1' heat wave definition, which takes the 97.5th percentile external air temperature as a threshold [17].

Armstrong's approach shows the need for a percentile based threshold which is adaptive for each region. However more work is needed, since high external air temperatures alone do not constitute the full risk to health, given the apparent temperature that a human body will feel is also dependent on humidity and heat gains from solar radiation [50]. Plus a temperature metric is needed that reflects an equivalent temperature for the indoor environment. For instance inside buildings, solar gains affect the internal temperature, and humidity can be high in well-insulated non-permeable structures.

4.4.1 Metrics for peak thresholds

Metrics described with peak thresholds will be analysed for occurrences of significant excess deaths in hot periods since 1983, which will allow comparative analysis to be undertaken. Establishing a metric and peak threshold for indoor health would give the building design industry the necessary temperature limits for human safety. The first part of this investigation will centre on the association between mortality and fixed temperature criteria described in the Bb101 guidance, using Met Office peak thresholds. Then more complex metrics such as TAPP and UTCI with percentile peak thresholds will be investigated with respect to coincident mortality rates.

The impact of hot weather on health indoors is examined by first searching for events of peak external conditions and comparing to coincident excess deaths, then relating external conditions to a metric for indoor conditions for a comparative analysis. Daily mortality data was obtained from the Office of National Statistics (ONS), which contained complete regional data sets from 1978 to 2011. From this data significant excess deaths were calculated by filtering the data for all deaths over two standard deviations above each region's three year running-mean for each day. Two standard deviations is taken in other epidemiological literature as a level of significance [106], [107]. Taking the regional running mean helped remove the underlying general trend in the gradual decline in death rates over the period, due to improvements in healthcare.

4.4.2 Creating a reference indoor environment

This thesis requires a reference building with an appropriate internal environment. The response of this building to the external weather depends on many factors including the form of the building. It is impossible to define a control building that can represent all possible buildings so a simplification must be made and a conceptual free-running building is used. CIBSE has described a reference conceptual building for use in its treatment of Design Summer Years in London, which is free-running and has an operative temperature equal to the external temperature [101]. The conceptual building in this thesis takes the same design and is similarly equivalent to a building with a high ventilation rate, so the internal humidity is equal to the external humidity and internal air temperature is equal to the external air temperature. The reference building design is a simple box room measuring 5x5m (width and depth) by 2.5m in height. It has one window centrally split with a bottom-up sliding design, like as a sash window, measuring 2m wide by 1m in height, allowing for the simulation of solar radiative effects, with 50% of the solar radiation at a given hour transmitted, as is realistic for a double glazed building. The air inlet is 0.1m in height and the full width of the 2m window and is located at the bottom of the window – this models a slightly ajar window, as would be typical of window use in a naturally ventilated building. The air outlet is located at the top of the window, with the same dimensions as the inlet, and this would be typically found in a vented window design. Airflow is driven by external wind conditions. This simple building does not contain any furniture, other objects or contents that contribute to internal heat gains.

Whilst this conceptual building is a clear simplification, and presupposes partial direct exposure to sunlight, it is simple to implement as external weather can be processed into the internal environment; other conceptual buildings may give different results but such implications are not the focus of this work. Capturing data from an increased set of weather parameters, and using solar radiative temperature alongside air temperature, humidity and wind speed, an attempt will be made to combine these variables so that the UTCI temperature can be calculated and used to inform a new heat stress metric for indoor use.

4.4.3 Preparing weather data

Weather data obtained from the British Atmospheric Data Centre (BADC) was used to create the internal environment using the conceptual building [108]. For some regions gaps in the data sets, due mainly to operational issues at weather stations, needed to be filled using interpolation algorithms. Where atmospheric weather data was found to be incomplete, algorithms were used to interpolate missing data using linear extrapolation for variables such as cloud cover and wind speed, whilst cubic spline curves were generated for temperature and atmospheric pressure [109], and solar radiation was interpolated using average hourly values for the corresponding cloud cover and sun path for the time of day [110]. Months with more than 20% missing data were not used, as they compromised the accuracy of interpolated data. Few weather stations had complete monthly data sets, so three locations with broadly complete data, and sited within different ONS regions to give a good geographic spread of urban areas were chosen: London, Birmingham and

Plymouth. The internal environment at these three locations was then compared to the mortality data for the corresponding time period to investigate correlations.

4.4.4 Establishing peak temperature threshold metrics

Aiming for greater correlation between the internal threshold temperature and mortality, ten indices were compared with significant excess deaths to find the most effective index for forecasting health risks inside buildings. The majority of the definitions tested use air temperature alone, whereas TAPP and UTCI are empirically derived. As we have seen in chapter 3, the 'Apparent Temperature' (TAPP) heat wave definition [111], used in the EuroHEAT study [53], uses both air temperature and humidity levels to establish the apparent temperature that a human body should 'feel', described in **Equation 3-5**. TAPP uses a percentile based threshold, rather than set temperatures. Percentile-based definitions potentially have the advantage of being able to take into account human adaptation to changes in climate over time [112].

Using the TAPP scale, a heat wave is defined as a period of at least 2 days with maximum daily T_{app} exceeding 97.5th percentile and T_{min} exceeding Met Office night thresholds during the period. Thresholds are established at the 97.5th percentile, and are calculated for each calendar day. From chapter 3, the UTCI combines wind speed, radiation, humidity and air temperature, and is defined as the air temperature of the indoor reference environment, which would produce an equivalent dynamic physiological response. The UTCI function was described in **Equation 3-6** [56], and the peak threshold metric represents the UTCI exceeding 97.5th percentile, as in the TAPP case.

Table 4-4: Ten peak threshold criteria for predicting significant excess deaths in hot weather

	Peak threshold metric description
1	Met Office: max air temp >32°C (daily maximum air temperature and night time temperature exceed regional thresholds e.g. 32˚C day, 18˚C night in London)
2	Tmax >31.5°C (daily maximum air temperature exceeds 31.5˚C)
3	Tmean >24°C (24 hour mean air temperature exceeds 24˚C)
4	Tmax >31°C (daily maximum air temperature exceeds 31˚C)
5	UTCI >97.5% (daily maximum UTCI temperature exceeds 97.5th percentile)
6	TAPP >97.5% (daily maximum apparent temperature exceeds 97.5th percentile)
7	Tmean >97.5% (24 hour mean air temperature exceeds 97.5th percentile)
8	Tmax >97.5% (daily maximum air temperature exceeds 97.5th percentile)
9	Tmean >23.5°C (24 hour mean air temperature exceeds 23.5˚C)
10	Tmax >30°C (daily maximum air temperature exceeds 30˚C)

Computer algorithms were written to scan for extreme internal environments from 1983 onwards which correspond to events of significant excess deaths.

The definitions were selected to give a good range of varying thresholds, and reflect international epidemiological research into heat wave mortality effects [113]. The ten peak threshold criteria are shown in **Table 4-4** and offer a mix of fixed peak thresholds similar to those used in the Met Office heat wave descriptions and Bb101 overheating guidance; peak percentile thresholds based on Armstrong's work; averaged 24 hour peak thresholds based on international thresholds and the inclusion of apparent (TAPP) and equivalent (UTCI) peak thresholds. Each of the above criteria are tested as two metrics, where peak thresholds were exceeded for one single day and where exceeded for two consecutive days (as per the Met Office heat wave definition). These metrics are not actual peak thresholds, rather possible indices for accounting for excess deaths. For the percentile-based thresholds 2.5% of all days will exceed the threshold, but it is the quality of coincidence of those days with significant excess deaths that will determine the most appropriate index.

4.5 Analysing mortality and coincident hot weather

4.5.1 Analysis of extreme hot events and mortality

The aim is to establish a metric for peak thresholds for internal environments, so that a proxy indicator for predicting excess deaths and issuing health warnings can be established. Investigation is required into the incidents of extreme external weather and coincident mortality. For this analysis fixed criteria were used similar to the current recommendations in Bb101 using the Met Office heat wave criteria as a benchmark for regional variations. Results for significant excess deaths during extreme weather are shown for the regions of London, Birmingham and Plymouth in **Table 4-5**. The Met Office criteria yielded four events in London that would have qualified as a heat wave externally since 1983, in Birmingham there were six, whilst in Plymouth there were none. To validate the Plymouth results, a manual investigation of the hottest summer in Plymouth (1995) revealed a single day when air temperature reached 30.2˚C, with overnight temperature hitting 21.9˚C. However, air temperature on the following day peaked at 27.3˚C, thereby discounting that period as a heat wave under current criteria.

Table 4-5: Number of significant excess deaths and Met Office heat waves externally since 1983 in three UK regions, identified using current Met Office heat wave health threshold temperatures.

Location	No. days when significant excess summer deaths occurred	No. of Met Office heat waves	Years with Met Office heat waves (and number of heat waves)	% Significant excess deaths occurring during Met Office heat waves
Plymouth	52	0	-	0%
Birming-ham	56	6	1989 (1) 1995 (1) 1995 (2) 2003 (1) 2006 (1)	8%
London	44	4	1990 (1) 1995 (1) 2003 (1) 2006 (1)	24%

The hottest consecutive period for the UK was found to be August 2003, and the internal environment for that period was analysed with the corresponding mortality data, and results are shown for Birmingham (**Figure 4-5**), London (**Figure 4-6**) and Plymouth (**Figure 4-7**). In early August 2003 all three locations were found to have a clear trend of high excess deaths. In Plymouth the temperature of this hot period reached 29.8˚C, but did not pass the threshold of 30˚C, and externally was not classed as a heat wave. In Birmingham temperatures over the same period exceeded 30˚C on three separate days, though none were consecutive. In London, temperatures exceeded 32˚C for 3 consecutive days. In London there were 44 days since 1983 on which significant excess deaths occurred, in Birmingham there were 56, and in Plymouth there were 52.

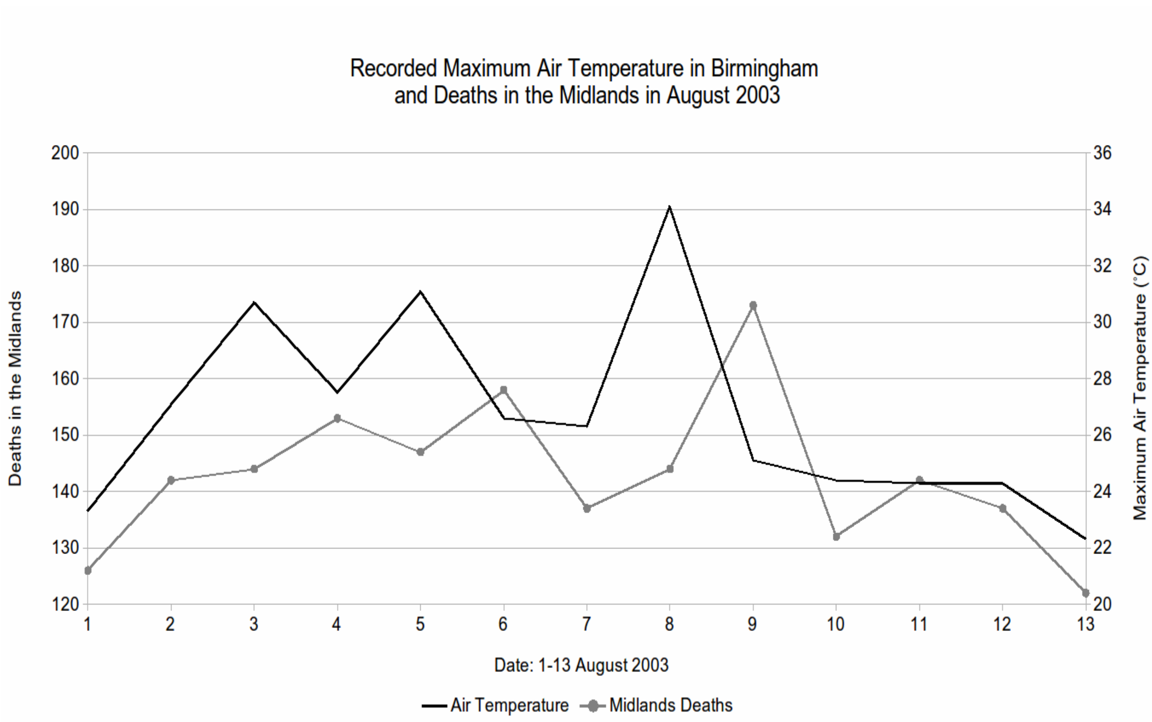

Figure 4-5: Recorded maximum air temperature and coincident daily mortality in Birmingham

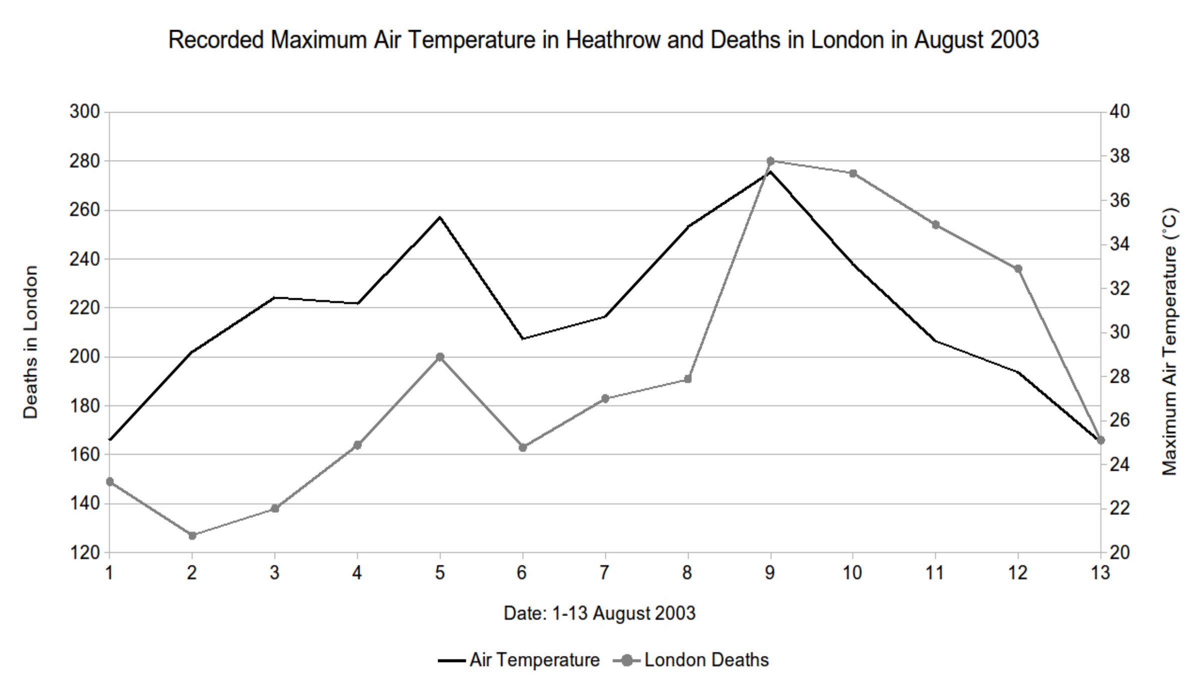

Figure 4-6: Recorded maximum air temperature and coincident daily mortality in London

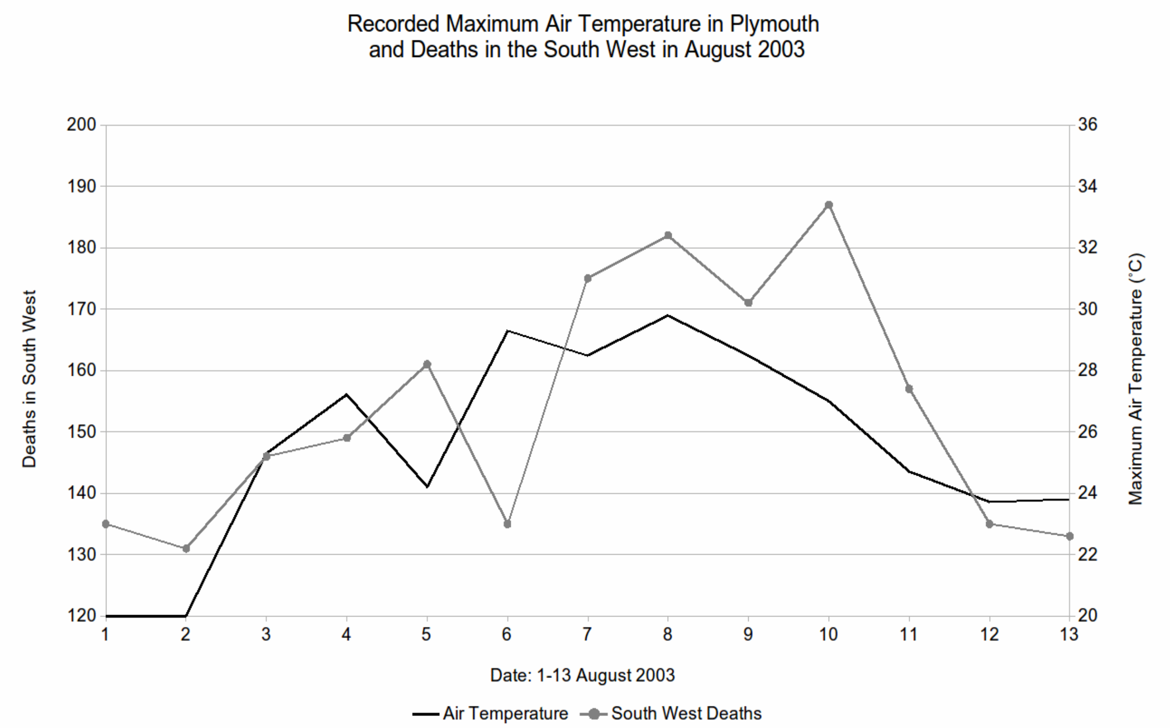

Figure 4-7: Recorded maximum air temperature and coincident daily mortality in Plymouth

Investigation of all data reveals a highly correlating relationship between temperature levels and excess deaths on the following day, indicating a potentially associative relationship with a one-day response lag, which has also been reported in other research [114]. Investigation of prior-day temperatures for all days on which significant excess deaths occurred was therefore undertaken. Analysis of the temperatures during these events looked at whether they exceeded the respective ten heat wave definitions on the same day or on the prior day to those deaths occurring. The full mortality plot for London can be seen in **Figure 4-8**.

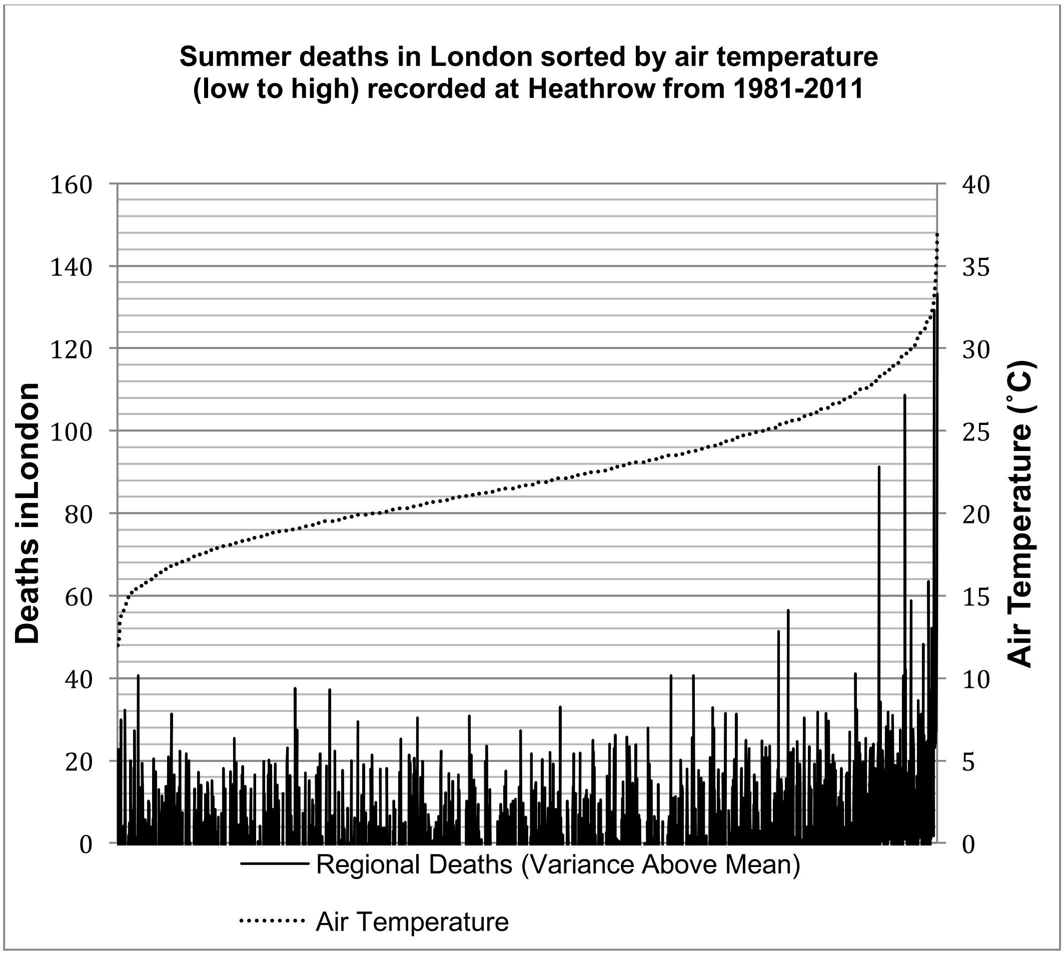

Figure 4-8: Air temperature and deaths in London

Results from extreme external events suggest a possible one day lag between high temperatures and an increase in mortality, and analysis of extreme internal events will reveal any correlation of this effect. The ten peak criteria definitions outlined in the method are now tested both for their accuracy in forecasting significant excess deaths internally, as a proxy for occupant dissatisfaction and for false triggers, which are defined as 'false positive' and 'false negative' forecasts. False positives are defined as incidents where peak threshold criteria have been met, yet without coincident occurrences of significant excess deaths, whilst false negatives are defined as incidents where peak threshold criteria have not been met, yet significant excess deaths have occurred. A balance is required such that the peak threshold criteria is high enough for there to be a significant risk to occupant health but not too high such that the impact on occupant health is underestimated. Naturally not all cases of significant excess summer deaths can be attributed to hot weather, however of all the significant excess deaths during the period analysed, 80.6% were found to occur on days where the daily maximum external air temperature exceeded 24˚C, which is the threshold at which excess deaths are shown to occur [105], [115]. In total, 17.5% of all days were recorded as having daily maximum air temperature exceeding 24˚C.

4.5.2 Analysing mortality with peak temperature threshold metrics

The mortality forecasting performance of each of the peak criteria metrics are shown from 1981-2011, with results for London shown in **Figure 4-9**, results for Birmingham shown in **Figure 4-10** and results for Plymouth shown in **Figure 4-11**. False triggers are the sum of false positives (not triggering when it should have triggered) and false negatives (triggering when it should not have triggered), and these percentage values are plotted on the y-axes. The percentage of correct forecasts, by which is meant days on which peak criteria metric thresholds were exceeded and coincided with significant excess deaths, is plotted as a 100-x value for all points on the x-axes of these graphs, such that a lower value is better than a higher value; in other words, the percentage of correct forecasts that were missed. The reason for this was to show a Pareto front for easier evaluation of the best performing metric, hence the best performing metrics should lie on the Pareto front. Each graph, plotted per region, shows 2 versions of the 10 peak temperature threshold metrics: one for same day and one for prior day (labelled as [metric]-1 e.g. Tapp-1).

The most appropriate peak temperature metric during hot weather should be the metric with a combination of the lowest percentage values of correct forecasts missed and with the lowest percentage of false triggers. In this respect, the UTCI metric UTCI>97.5th percentile for same day forecasts performed best with 34% correct positive forecasts of days of significant excess deaths in London. The regional plots show that the Tmax>30˚C metric, equivalent to the Met Office threshold, correctly forecast most frequently, along with the Tapp>97.5th percentile metric, albeit with higher values for false triggers than UTCI>97.5th percentile. However, for Birmingham and Plymouth Tmax>30˚C show very different results, leading to the question of its reliability as a metric for use in other UK regions, and compromising its overall mortality forecasting performance. The UTCI>97.5th percentile metric balanced the two criteria of correct forecasts and fewest false triggers more consistently than the other metrics.

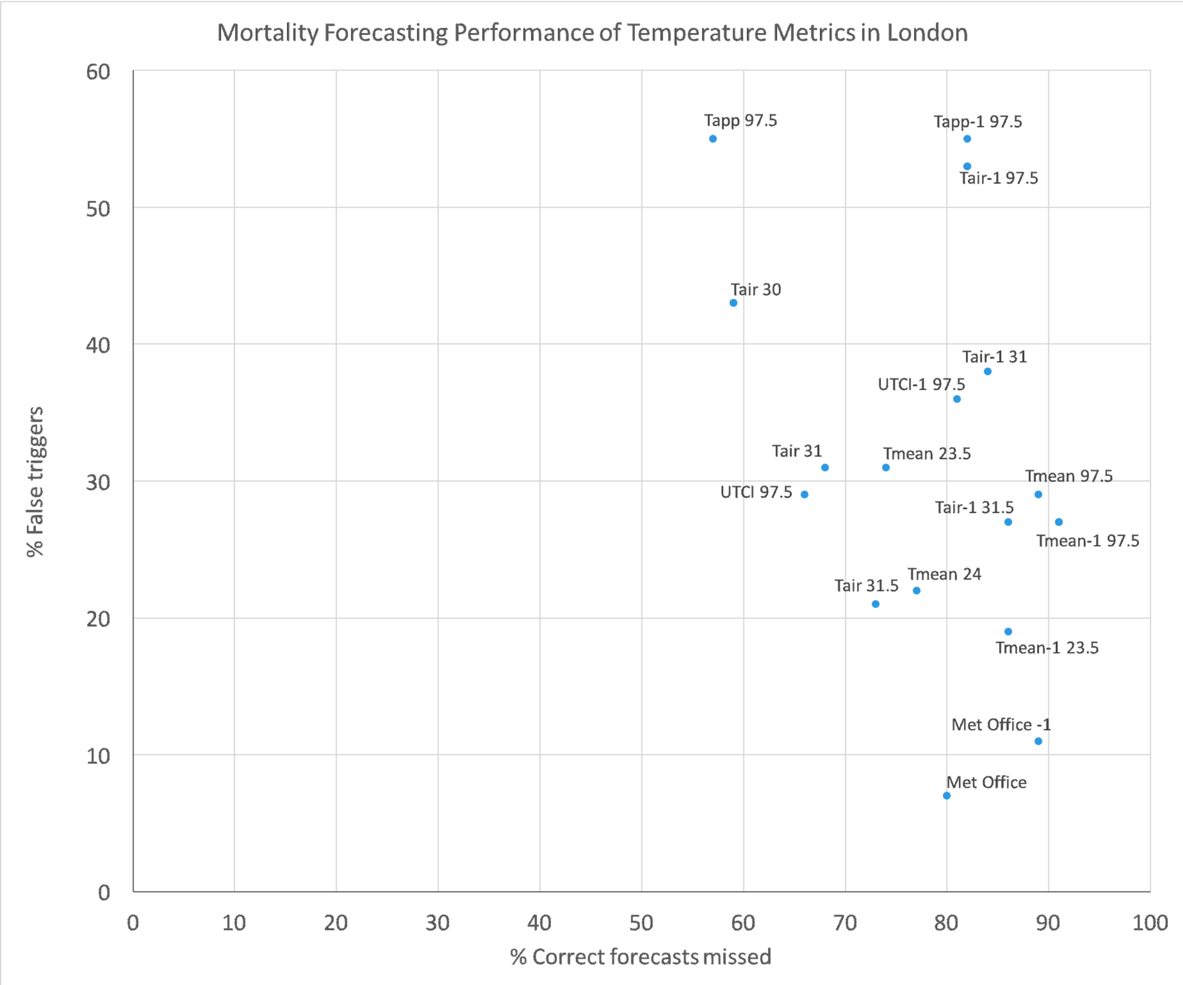

Figure 4-9: Mortality forecasting performance of temperature metrics at peak thresholds in **Table 4-4**, plotted for % false triggers (lower is better) and % correct forecasts that were missed (lower is better) for London 1981-2011.

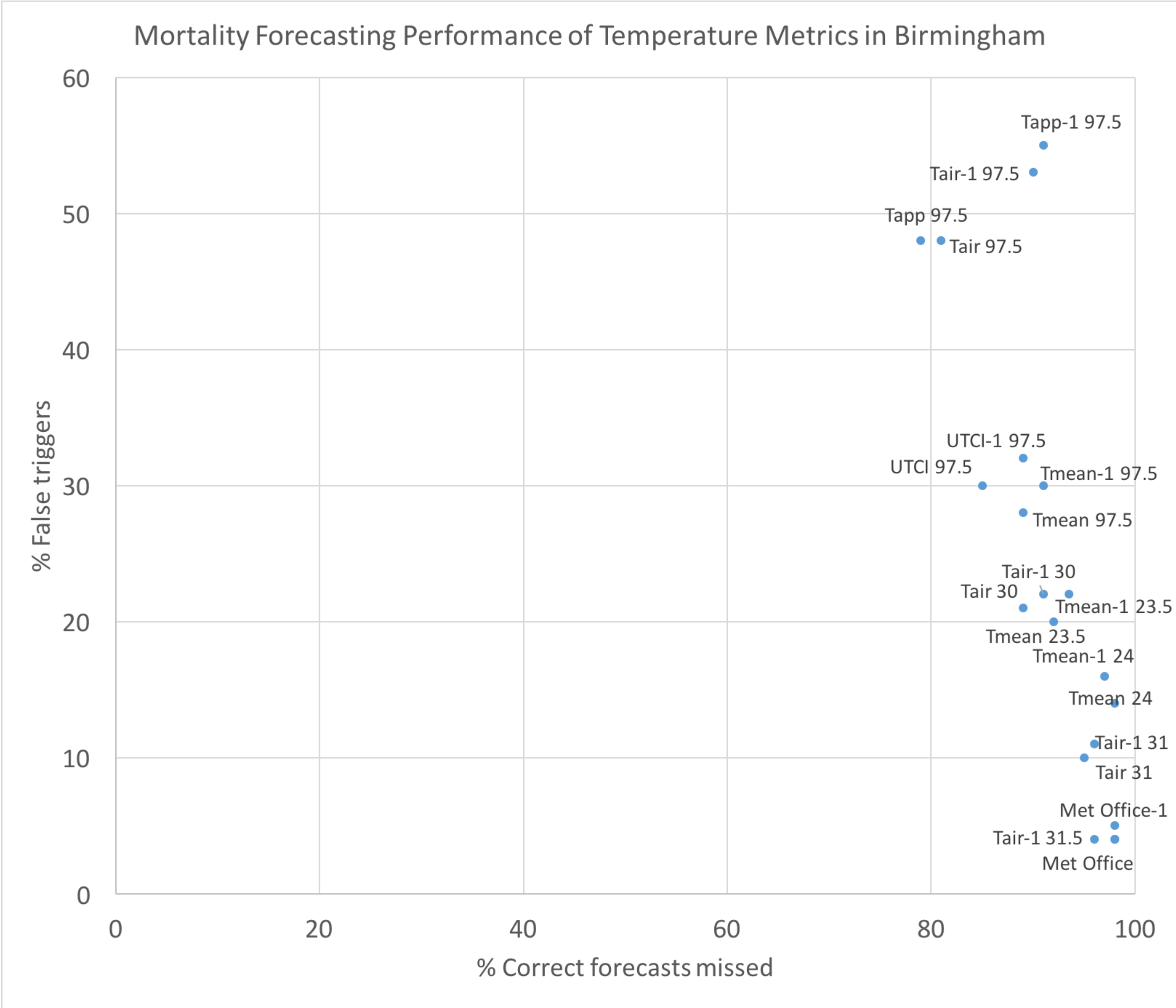

Figure 4-10: Mortality forecasting performance of temperature metrics at peak thresholds in **Table 4-4**, plotted for % false triggers (lower is better) and % correct forecasts that were missed (lower is better) for Birmingham 1981-2011.

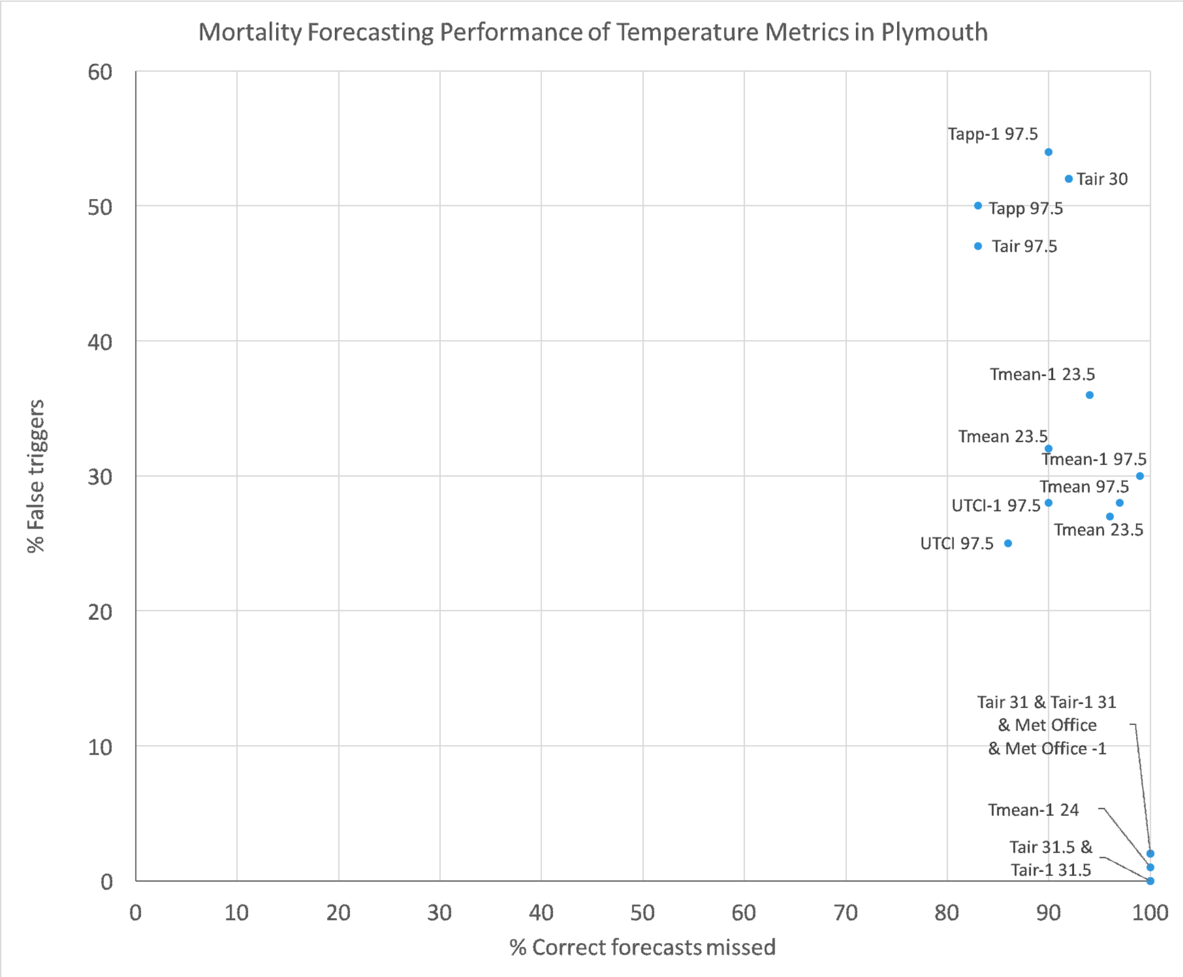

Figure 4-11: Mortality forecasting performance of temperature metrics at peak thresholds in **Table 4-4**, plotted for % false triggers (lower is better) and % correct forecasts that were missed (lower is better) for Plymouth 1981-2011.

Significant excess deaths of two standard deviations above the mean were found to occur at around the 97.5th percentile of daily maximum temperatures, after single day breaches in temperature thresholds. The majority of all significant excess deaths (80.57%) were found to occur during unusually hot weather (>24˚C). Significant excess deaths were found to occur on 61 days over the period and five of those days were coincident with Met Office heat wave periods and 20 were coincident with UTCI ‘hot days’.

On days when significant excess deaths were preceded by these 'strong heat stress' UTCI temperatures, they did so with a one day time lag, indicating rises in mortality rates follow a day after hot weather, as has been shown in other literature [116].

4.5.3 Population cohorts and human health metric considerations

The mortality data received from the ONS was not filtered for age groups, and it should be acknowledged that more detailed results would have been achieved if the ability to analyse the effects of hot weather on varying population cohorts had been possible, since several studies have shown greater mortality rates in elderly cohorts during heat waves [27]. This thesis focuses on mortality in heat waves to assess health risk in the indoor environment, rather than on hospital admissions in hot weather events, which could potentially have provided richer data about the demographic of vulnerable hot weather victims. Other works have reported no significant increases in admission rates during hot periods [117], and so mortality was deemed a better measure of health impact. One further consideration to take into account is that weather data is sourced from site-specific weather stations, and that the recorded values for the UTCI (air temperature, humidity, wind speed and solar radiative temperature) are most accurate at the specified weather station location. Therefore there is some regional generalisation applied to that weather data in order to perform analysis against regional mortality; for instance London weather data is collected at Heathrow airport, which is on the geographical fringe of London, and possibly does not give an accurate enough representation of London weather. These are limitations to the model and so should be discussed in future work.

4.6 Adopting the UTCI heat stress metric

4.6.1 Mortality forecasting with the UTCI metric

From earlier in this chapter we know that buildings are currently tested for comfort using benchmark air temperatures in 'unusually warm' weather. One of the goals of this thesis was to investigate other indices that could provide a regionalised metric for assessing the impact of extreme weather conditions on the internal environment and human health within buildings in order to establish what the peak threshold should be. The UTCI metric for health in buildings, using a 97.5th percentile-based temperature threshold, predicted excess mortality with better accuracy than other indices tested.

For context an analysis was conducted into recent weather and mortality for London. Since 1983 there have been 2115 significant excess deaths during the summer period in London. Using the UTCI metric for this period results in peak threshold days that are coincident with 897 significant excess deaths. Using the Met Office heat wave threshold there are 4 peak threshold periods coincident with 515 significant excess deaths. On days where significant deaths did not coincide with UTCI temperatures that exceeded the target threshold, UTCI still remained within a range of of 30.5-32.7˚C, which fall into the ‘strong to very strong heat stress’ bands on the UTCI scale. High air temperature heat wave criteria, such as the Met Office definition, correspond to more deaths during the hottest periods, but are not triggered in conditions where air temperatures are slightly lower yet other weather parameters combine to produce an environment inside buildings that results in a significant health risk. There is a need to balance the number of peak threshold days and health risk forecasting accuracy, however, given that there are in fact 48 days of significant excess deaths, the most accurate definition would register 48 incidents and capture every significant excess death event. This is not possible, since not all excess death events can be attributed to hot conditions inside buildings, however the definition, which comes closest in this respect, uses the UTCI index. Similarly to adaptive comfort this peak threshold could be adjusted with respect to the occupant demographic and for vulnerable occupants such as in care homes and schools. Internal UTCI temperatures on days with significant excess deaths reach an average of 30.5-32.7˚C, which fall into the 'strong to very strong heat stress' bands on the UTCI scale. Externally UTCI temperatures in full sun reach 36-42˚C (depending on the location), representing equivalent 'very strong heat stress' on the UTCI scale. In this work, metric testing was conducted against mortality. Deaths in hot conditions are generally (but not in all cases) attributed to the most vulnerable, and so the peak threshold criteria assessed in this work likely apply to the most vulnerable people.

4.6.2 Adapting building thermal performance guidelines

Maximum air temperature on days with significant excess deaths fell within a range of 29-36˚C. If this were the maximum temperature range resulting from CIBSE TM52 calculations [72], the running mean temperature is 13–36˚C.

Criterion 3 of TM52 states that a building will overheat (and thereby fail an assessment of its thermal comfort) if:

$$\Delta T > 4^{\circ}\mathrm{C}$$

Equation 4-1

where

$$\Delta T = T_{operative} - T_{max}$$

Equation 4-2

and where

$$T_{operative} = 0.5T_{air} + 0.5T_{solar}$$

Equation 4-3

and

$$T_{max} = 0.33T_{running\ mean} + 21.8$$

Equation 4-4

Results from this thesis show that on days when significant excess deaths occurred ΔT for maximum air temperature averaged 0.5–2.7˚C across the regions. This suggests that for criterion 3 of CIBSE TM52 (**Equation 4-1**) ΔT should be no greater than $3^{\circ}\mathrm{C}$.

CIBSE's own guidelines were recently revised to broaden overheating criteria to include severity and an absolute limit, though thresholds are still based on air temperature alone and the absolute limit of 4°C above the indoor adaptive comfort temperature, results in practice in temperatures broadly similar to the Bb101 indoor limit [72], which are arguably too high, based on the finding that

ΔT should be no greater than $3^{\circ}\mathrm{C}$. Current thermal comfort guidance for modelling buildings is already moving towards regionalised thresholds as given by adaptive comfort models in CIBSE's recent TM52 guidelines. However, a percentile-based criteria incorporating the full set of environmental parameters that affect human heat stress has yet to be established for the peak threshold. The UTCI metric developed here uses parameters that are typically output by building models, so would be straightforward to implement for a more appropriate peak threshold for human health in buildings. The use of which is similar to the current metric of 'internal temperatures should not be greater than 32˚C' as in this work there would be significant health risks to people if the threshold is exceeded.

4.6.3 Using the UTCI metric for heat wave planning

The present formulation of a heat wave definition solely based on the air temperature index with static thresholds is simplistic. Further work should identify the most suitable heat wave or hot day definitions to be used in future risk analysis work. Factors to be considered are which weather variables, or combination of weather variables should be selected, the threshold temperature as either a static or percentile value and the length of time the hot weather should last for a warning to be declared. Clearly processes for identifying temperature thresholds for health risk are dynamic and dependant on multi-variable weather parameters. For temperate climates such as the UK, where the UTCI metric shows good results for forecasting heat related health risk inside buildings, the UTCI metric could be used in conjunction with standard weather reports and national heat policies to give people additional localised information to monitor the indoor environment for potential health risks. Since the UTCI uses the Degree Centigrade index, it would be familiar and comparable.

Results from this chapter indicate that too few heat wave warnings are currently issued compared to the number of days of significant excess summer deaths. Single hot days of UTCI temperatures exceeding the 97.5th percentile, equivalent to 'strong heat stress' on the UTCI scale, put public health at risk. A health warning system using UTCI >97.5th percentile threshold most accurately forecasts significant excess deaths in hot weather without giving too many false positive warnings. New heat wave definitions should be considered to account for the full set of environmental parameters that affect human health. A possible UTCI warning system, equivalent to the current Met Office heat wave plan is outlined in **Figure 4-12**.

All weather variables that make up the UTCI are forecast by the Met Office, so evaluating the UTCI temperature would be simple to implement, with warnings issued similarly to the wind chill index as used in winter. Since the threshold temperature is based on a running mean percentile, unlike the current static temperature threshold, the warning system would be future proof. Given the staggering rise in hot weather conditions we are likely to face, developing accurate weather warnings for the future is paramount.

Level 1: Green — Summer preparedness and long-term planning

This is the minimum state of vigilance during the summer. During this time social and healthcare services will ensure that all awareness and background preparedness work is ongoing.

Level 2: Yellow — Alert and readiness

Triggered as soon as the risk is 60% or above for maximum daily UTCI temperatures to reach the 97.5th percentile threshold in one or more regions on a future day. This is an important stage for social and healthcare services who will be working to ensure readiness and swift action to reduce harm from a potential heatwave.

Level 3: Amber — Heatwave action

Triggered when the Met Office confirms the UTCI daily maximum temperature forecast for the next day has a greater than 90% confidence level that the 97.5th percentile threshold will be met for one of more regions. This stage requires social and healthcare services to target specific actions at high-risk groups.

Level 4: Red — National Emergency

Reached when a UTCI heat wave is so severe and/or prolonged that its effects extend outside the health and social care system. At this level, illness and death may occur among the fit and healthy, and not just in high-risk groups.

Figure 4-12: Possible UTCI heat wave action plan flow path, based on the current Met Office heat wave plan [12]

4.7 Chapter summary

In this chapter an overview is given on thermal performance modelling and how current building designs have the potential to suffer from overheating in hot weather. Hot days and heat waves are analysed alongside mortality rates and results show that the UTCI with a 97.5^{th} percentile threshold is the most appropriate metric for predicting significant excess deaths in hot weather. New temperature thresholds for the indoor environment are also established, including a revision of Criterion 3 of CIBSE TM52. The UTCI is shown to be a capable metric for determining peak thresholds for the indoor environment. As a universal index this work could be extended to other countries, since it has the potential to become a useful international tool for both thermal comfort in buildings and human biometeorology [62]. The success of such work would depend on the availability and accuracy of locally recorded weather data. Analysis of future hot weather will be undertaken in the next chapter, in order to investigate the trends in frequency and intensity of heat waves to come, which will enhance understanding of future risks and help international adaptation strategies [73]. The following chapter will explore future climates and future weather and use the UTCI metric to scan for near-extreme and extreme conditions. The current reference weather years that are used to simulate indoor thermal conditions will be updated to include the UTCI for current and future climates.

5 Overheating in future climates

5.1 Creating future weather

Researching future annual heat wave frequency growth is an important task. Not only does this work aid building engineers, but also assists public health policy and adaptation strategies [118]. Regarding predictions of future extreme weather, studies have thusfar taken current heat wave concepts and maximum air temperature metrics, returning growth forecasts of future hot weather based on air temperature alone [13], [119], [120]. This chapter explores methods for creating future weather and presents results for hot weather growth trends for use in building modelling in particular.

5.1.1 Weather generating

There are two methods of creating future weather. The first is to use a weather generator, the second is to use morphing techniques [121]. The following examination of both these methods should indicate which technique is more suitable for creating weather for heat wave analysis. UKCP09 has a stochastic weather generator, which creates hourly and daily weather variables at a 5km resolution, based on IPCC climate projections [122]. The weather generator uses statistical relationships between observed climatic variables, and these relationships are stretched using climate projections to produce future time series on a daily and hourly basis. The weather signal, which is used to generate this time series, is based on a stochastic rainfall model [123], and the rainfall states are used to generate other weather variables. The rainfall states considered in the weather generator are:

- Dry today / dry yesterday
- Wet today / wet yesterday
- Dry today / wet yesterday
- Wet today / dry yesterday
- Dry today / dry yesterday / dry day before

The weather generator produces several weather variables for the signal: precipitation, maximum air temperature, minimum air temperature, percentage of sunshine, vapour pressure, relative humidity, direct solar radiation, diffuse solar radiation and potential evapotranspiration. In addition, to create a weather file, wind speed, wind direction, air pressure and cloud cover are also needed.

5.1.2 Weather morphing

An alternative to stochastically generated future weather is to take historically recorded weather and morph it. An advantage of using morphing is that the underlying weather sequences are real rather than modelled weather, with the modelling uncertainty only coming in through the average changes. The morphing procedure uses the ‘baseline climate’, defined as the averaged present-day weather sequence. Weather variables are morphed over weather time series of one month, as this time period fits the highest change factor resolution in UKCP09, and the morphing technique adjusts the time series to produce weather with new values that are aligned with the change factors, whilst retaining comparable short-term variations. There are three types of morphing algorithms: 'simple shift', 'simple stretch' and 'weighted stretch' [124] [125], The choice of morphing algorithm is dependent on the weather variable,

The shift operation changes all values by the same amount, whilst a stretch changes a larger value by a proportionally larger amount. The shift operation adjusts only the mean of the time series and a stretch operation adjusts both the mean and the variance of the time series; this consequently results in an adjustment in the relative magnitudes of extremes in the time series. The 'simple shift' algorithm is given by **Equation 5-1**:

$$\bar{x}'_m = \bar{x} + \Delta\bar{x}_m$$

Equation 5-1

where the adjusted time series *x'* is a function of the original time series *x* and $\Delta\bar{x}_m$ is the change in the monthly mean of the variable. The shift operation is used in climate change scenarios that project an absolute increment in the monthly mean value. The 'simple stretch' algorithm is given by **Equation 5-2**:

$$\bar{x}'_m = \alpha_m\bar{x}_m$$

Equation 5-2

where α_m is the fractional change in the monthly mean value of the variable. A combination of a shift and a stretch is used if an adjustment is required for both the mean and the variance, for instance in the daily mean and the maximum and minimum daily air temperatures, given by **Equation 5-3**:

$$\bar{x}'_m = \bar{x}_m + \Delta\bar{x}_m + (1 + \alpha_m)(\bar{x} - \bar{x}_m)$$

Equation 5-3

For some weather variables it is not appropriate to use just the 'shift' or the 'stretch' algorithms. For instance the stretch factor for the 'simple stretch' algorithm is constant for each month, and it is useful to have a weighted stretch factor that is a function of the prevailing weather conditions over time. The morphing algorithm created for this case was the 'weighted stretch', given by **Equation 5-4**:

$$x' = x + \left[\frac{(T_{mean} - T_{min})}{(T_{max} - T_{min})} \times \left[\frac{(T_{max} - T_{min})}{(T_{mean} - T_{min})} - 1\right]\right] x^m (1 - x)^n$$

Equation 5-4

where *m* and *n* are the weighting fractions and *T* is the external temperature.

Further developments of the morphing algorithms were introduced in TM49, and now all variables that can be morphed from UKCP09 use the weighted stretch, since the simple shift and stretch algorithms just maintained the changes to the diurnal cycle, rather than accounting for the prevailing weather conditions. These variables include dry bulb air temperature, relative humidity and cloud cover. Relative humidity is initially derived from wet bulb temperature observations, and is then morphed using the weighted stretch, this morphed relative humidity value can then be used to derive a new wet bulb temperature. Solar radiation for global, direct normal and diffuse values is derived using the cloud cover radiation model, since cloud cover is already morphed using the weighted stretch [110]. For dry bulb air temperature the weighted stretch algorithm is used, with the mean temperature and diurnal temperature (T_{max} - T_{min}) treated as two separate parameters [126]. It is important to check for unrealistic maximum temperature values, which can occur whilst maintaining the diurnal cycle with temperature. In some cases the weighted stretch algorithm is found to produce unfeasible values, for instance where new mean values are greater than new maximum values. In these scenarios the simple shift algorithm in **Equation 5-1** is used instead. All environmental variables calculated from constituent weather variables are derived if the constituent variables are found to have changed.

For the purposes of this thesis it is important that the weather extremes are preserved as realistically as possible, and this factor primarily informs the choice of method for creating future weather. The weather generator takes cumulative frequencies of weather observations and uses a statistical signal to then stochastically produce future weather based on the change factors. The weather generator has a number of advantages, including the ability to create wholly new data sets not encumbered by missing data issues from historical weather records, because it uses averaged data. The morphing technique also takes cumulative frequencies of weather observations to create new weather based on the change factors. Statistically the climate should be similar, however, since the weather generator is built to use averaged data, and the morphing technique ‘morphs’ each data point, the result is that the weather generator is less able to handle the tail-end percentiles [121], and since these are where the extremes lie, future weather data created in this fashion is unlikely to be suitable for use in testing extreme weather effects on buildings and health. Since the morphing technique uses data points from observed weather, the extreme values are preserved in line with empirical observations, morphed with the change factor adjustments, avoiding the potential for anomalous extreme values that could skew and invalidate the work in this thesis. It is for this reason that future weather created using the morphing technique was chosen as the source data for investigating hot weather and the health effects in buildings. Generated maximum temperatures were also checked against the maximum temperatures reported in UKCP09, and were closely matched.

Using the morphing method with the high emissions scenario, future weather files are created from a base empirical data set of weather recordings, resulting in a series of possible versions of 30 years of climate data. For each future era of the 2030s, 2050s and 2080s 10,000 versions of a full calendar year hourly weather data are created, each representing a different yet equally likely possible future scenario [73], [127].

5.2 Analysing future extreme hot weather

Computer algorithms to detect heat waves were written in *MathWorks MATLAB* [128] and applied to current and future weather data to search for two day heat wave events and individual 'hot days' using the Met Office maximum temperature metric and UTCI metric. For future weather the number of annual heat waves was found by division over the 30 sample years and a percentile range of annual frequencies was given. Heat wave results from the current period, along with the probabilistic heat wave results from future projected climates were then plotted together to visualise the trend. Statistical uncertainty inherent in any forecasting method means that there is greater uncertainty in predicting a series of consecutive hot days constituting a heat wave than there is in predicting the frequency of individual hot days [129], so an analysis of hot days gives a potentially more accurate assessment of the growth trends of extreme conditions. 'Hot days' are defined as single days that breach heat wave thresholds and exclude any consecutive time conditions or night temperatures. A hot day occurs when daily maximum air temperatures exceed 32˚C in London, and when UTCI temperatures exceeds the 97.5th percentile of the baseline weather data, (equating to a UTCI temperature of 32.4˚C).

5.2.1 Analysing future heat waves and hot days

Current and future annual heat wave frequencies are shown as a plot in **Figure 5-1** and **Figure 5-2**. Future heat wave frequencies are given as a box and whisker plot range, and values are shown for the significant percentile points within the probabilistic data ranges (the baseline results from chapter 4 are shown as established values for the date period labelled '2000s'). All ranges for both Met Office and UTCI indices had an expected minimum value of 0 heat waves per year. Maximum limits based on a 99th percentile of the data range gave diverging values as expected in line with the uncertainty in the UKCP09 climate projections. There were no significant outlying points in the results and values along the percentile range appeared controlled, indicating robustness of the model and method.

Mean annual heat wave frequency for both Met Office and UTCI definitions showed an upward trend, with Met Office style heat waves predicted to be the norm by the 2050s and frequent, between 2 and 3 per year, by the 2080s. Based on these figures, this would be an increase of 17.5 times the current frequency by 2080. The results of the increasing UTCI heat wave frequency in **Figure 5-2** show these are currently experienced at a rate of around one every two years, but this could grow to around 2 per year by 2030. There could be around 5 hot weather events per year by 2080, which is an increase of 10 times the current frequency. The 97.5th percentile UTCI temperature for the current climate is 32.3˚C, which is classed as 'strong heat stress' on the UTCI scale, and by 2080 this could become 36.4˚C; a rise of over 4˚C in the threshold temperature over that period, representing 'very strong heat stress' on the UTCI scale.

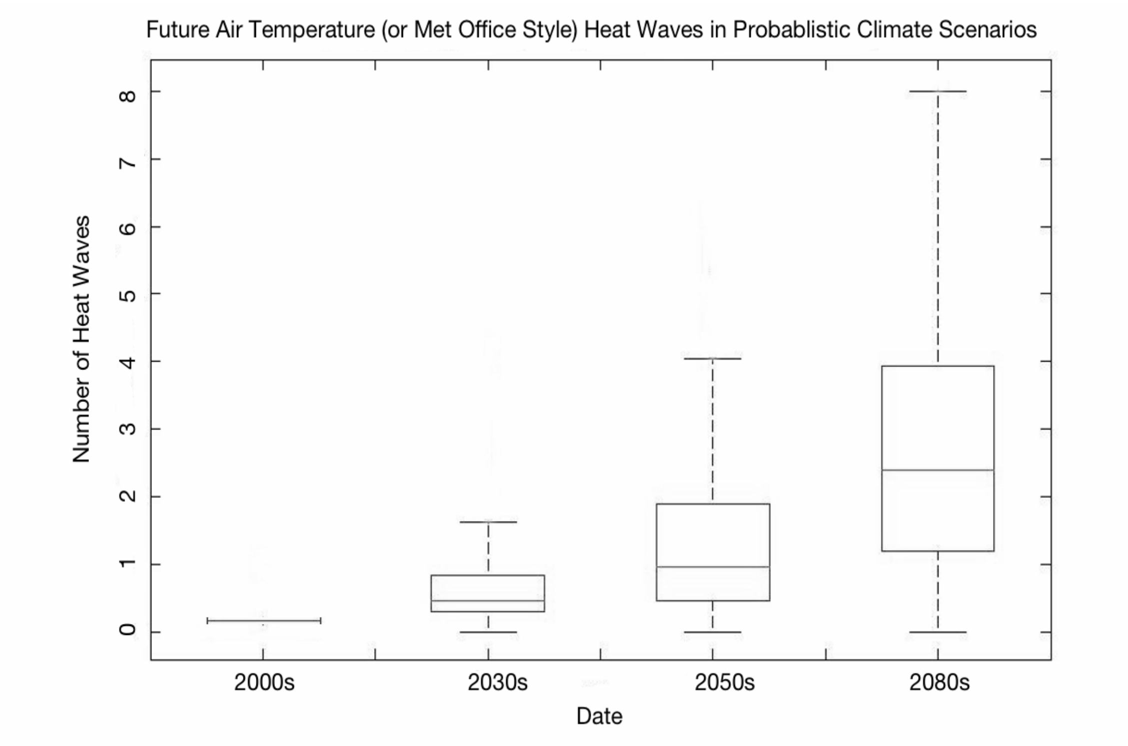

Figure 5-1: Number of annual Met Office heat waves in London. 2000s, 2030s, 2050s, 2080s

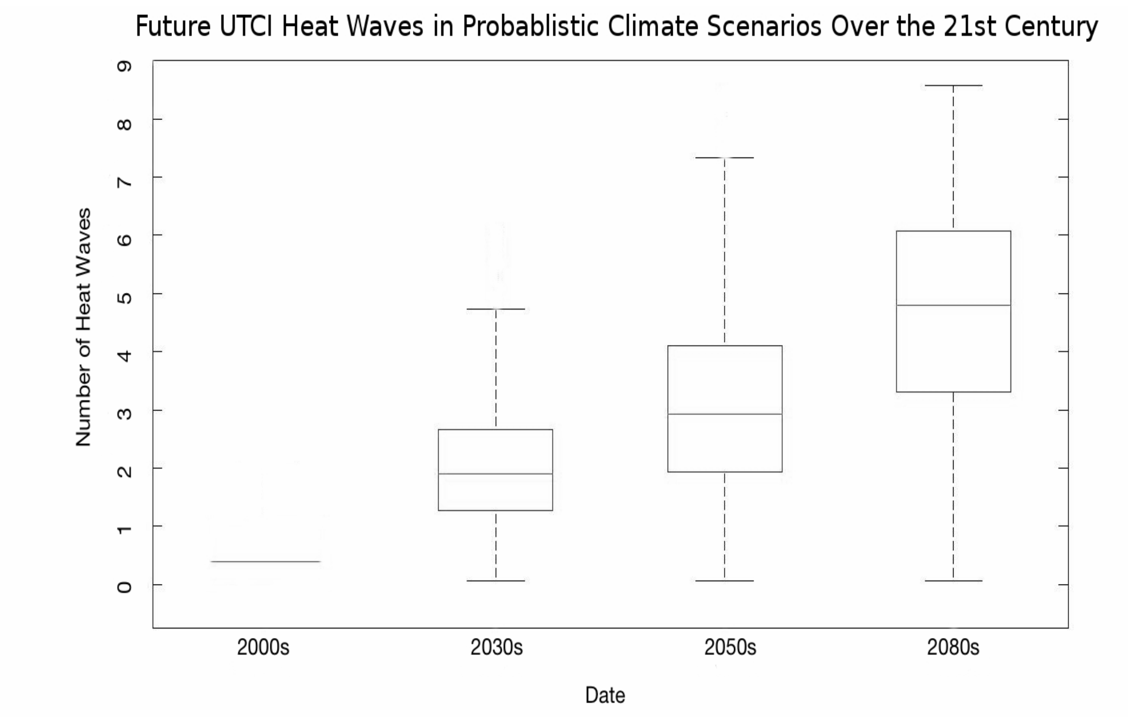

Figure 5-2: Number of annual UTCI heat waves in London. 2000s, 2030s, 2050s, 2080s

For the single hot day analysis, plots are shown in **Figure 5-3** and **Figure 5-4**. Met Office hot days are currently occurring at less than one per year. By 2030 there could be around 3 per year. By 2050 approximately 5 hot days could occur each year, and by 2080 around 12 per year. Overall growth between now and 2080s could be 14 times the current number. The number of UTCI hot days currently experienced is just over 2 per year. By 2030 this could rise to 7 days per year and approximately 13 per year by 2050. By 2080 around 23 UTCI hot days could be expected per year. Overall growth of UTCI hot days between now and 2080s could be around 10 times the current number.

Studies of heat waves up until this point have generally equated to the study of days with high air temperature, and have by and large used incomplete weather data sets [17], [130]. The large weather data sets and robust weather morphing model used in this study gave results that were well controlled and the model exhibited robustness given the context of large climatic uncertainty, especially since heat waves appear at the extreme ends of a probabilistic data range. Met Office heat waves are predicted to rise by 17.5 times by 2080, and single hot days could rise by 14 times. UTCI heat waves and hot days were predicted to rise by 10 times by 2080. This means that whilst the UK can currently expect 2 or 3 days of weather conditions per year conducive to causing human heat stress and health risks, by 2080 this could rise to the equivalent of nearly a month per year.

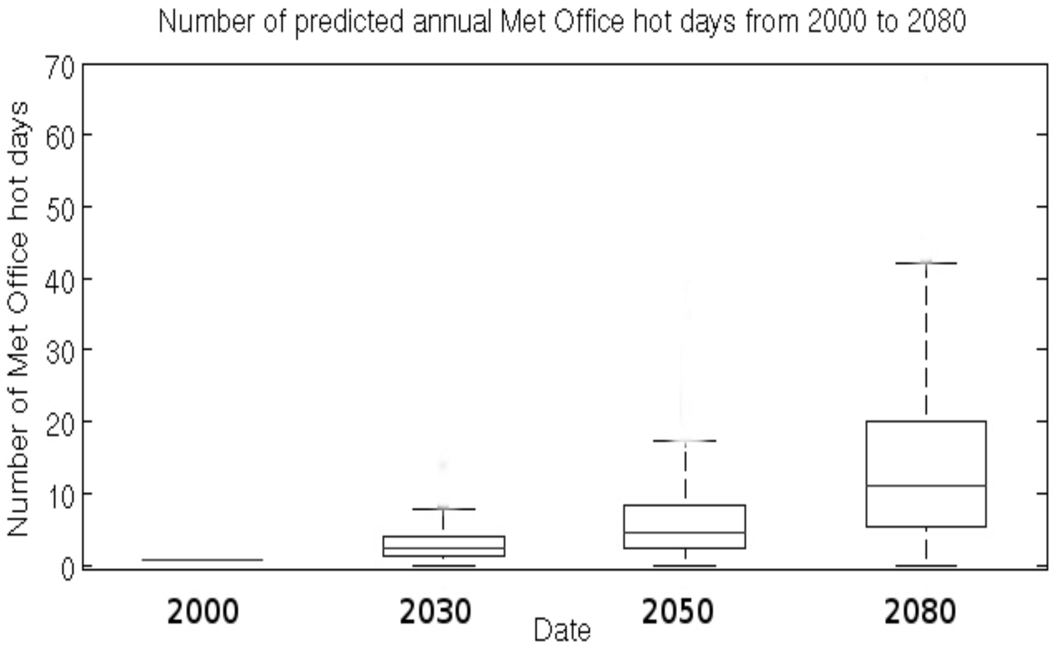

Figure 5-3: Number of Met Office hot days per year. 2000s, 2030s, 2050s and 2080s

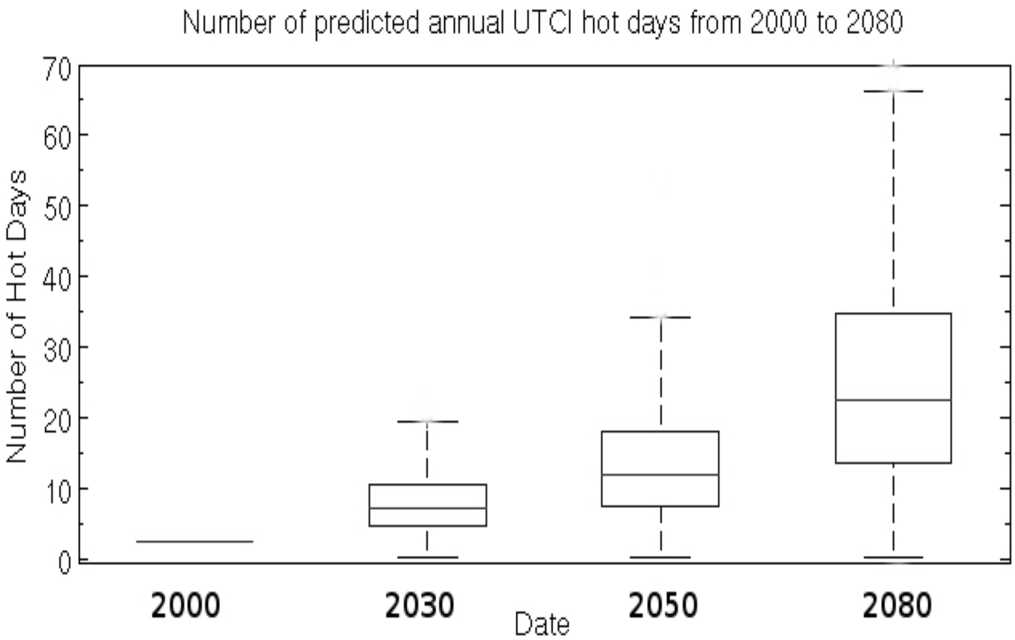

Figure 5-4: Number of UTCI hot days per year. 2000s, 2030s, 2050s and 2080s

The probabilistic nature of this work means that it is impossible to give precise numbers, and that forecasting uncertainty rises the farther into the future one looks. However the likelihood is that there will be between 1 and 4 heat waves exceeding current thresholds annually by 2080. It is also possible to analyse the future equivalent temperatures of a current heat wave or hot day. If instead of using current temperature percentiles from today's climate, future temperatures were used to define the running percentile threshold temperatures of future heat waves and hot days, then it can be shown that the UTCI 97.5th percentile in the 2080s could be expected to exceed 36˚C; well into the 'very strong heat stress' band on the UTCI scale.

5.2.2 Implications of future extreme hot weather

The rapid growth in the number of annual heat waves outlined in the results is a cause for concern, especially for health professionals, although this should be tempered somewhat by bearing in mind that these future heat wave predictions are based on current definitions of a hot weather event, and that thermal adaption to future climates will occur to some degree, lessening the overall impact. Factors such as climate adaption are not treated in this work, since it is difficult to predict the human body's propensity to adapt to such a degree over that time scale, however the figures outlined here show at least a worst-case scenario for building overheating and indoor heat stress. The question of climatic adaptation and to what extent people are capable of adapting is very much a developing research area [75]. It has been argued that people possess the ability to adapt to very harsh environments, and will continue to do so even in extreme climate change scenarios [131]. However, studies have shown that there is a possible limit to human adaptability [132]. Extremely high air temperatures are rarely coupled with high humidity, and so many parts of the world considered to have hot climates actually exhibit broadly comparable apparent temperature values with other parts of the world. This is key to understanding how people can inhabit these places, and key to understanding that thermal adaptation, at least with regards to apparent temperature has its limits. In other words, regardless of where people live or how acclimatised they are, people will not be able to adapt indefinitely, and it cannot be understated that however much our bodies acclimatise to such conditions in the future, the predicted UTCI heat wave and hot day conditions found in this thesis will feel a great deal hotter than they do currently.

5.3 Redeveloping the reference weather years

Engineers concur that thermally testing buildings in future climates should be carried out and that more weather variables should be used in overheating tests [133]. In order to test overheating effectively, building designers will need an appropriate temperature metric and suitable reference weather years to thermally test building models against current and future near-extreme and extreme conditions. They should also be aware of the trends in annual heat wave frequency, that have been analysed in this chapter, to understand the nature of the extreme weather that buildings will be increasingly exposed to.

It is important to recognise that assessing the thermal performance of buildings using reference weather data from the current climate will not hold as good practice as the climate changes, since a consequence of climate change is a divergence in weather patterns from current norms and an increase in extreme weather, with heat waves in particular rising in frequency [11]. Extreme weather already causes difficulties for the built environment, and with the possibility that these conditions could become the norm, engineers may need to respond by incorporating this type of weather into their building performance simulations. Using present comfort criteria, it is still possible for a building to be exposed to heat stress levels of high temperatures and still pass a thermal performance test. TM52 criterion 1 permits a building to overheat by up to 1 K for up to 3% of occupied hours (this would represent over 100 hours in a residential home between May-September); it is quite possible for a dangerous hot event to have a shorter duration than this, meaning a building could pass criterion 1 and still pose a health risk. TM52 criterion 3 allows for the upper value to be 4 K higher than the indoor operative temperature, which has been shown to be higher than the point at which heat stress occurs. The daily weighted exceedance value in criterion 2 is likely to be exceeded in an overheating case, so it is quite possible for a building design to fail criterion 2, but pass criterion 1 and criterion 3, which would mean that it satisfies 2 of 3 of the criterion tests and therefore passes the thermal performance assessment overall.

There is clearly a need for investigating the effects of more than just temperature on the selection of design hot weather data, and for reformulating reference weather years, so thermal modelling can be carried out at the building design stage using both near-extreme and extreme weather data. Extreme reference years may need to contain at least one heat wave and some longer periods of above-average hot weather, and reference weather years may need to be simulated, rather than derived empirically, to overcome the problems of missing data.

5.3.1 Probabilistic reference weather years and return periods

Current methods of assessing overheating are moving toward using probabilistic reference weather years in building modeling, and a recent paper has proposed new DSYs employing a reformulation method that takes into account the return periods of weather with high daily air temperatures to correct the inaccuracies for the current climate [101]. Redevelopment of the DSY in this form gives building modelers the option of selecting a reference year of weather data based on the likely return period of whichever level of hot conditions they wish to test. For instance the current DSY is found by taking the 'third hottest' year for each geographic region from recorded data over a 21-year period [134]. A probabilistic 'third hottest' DSY would therefore have a return period of 1 in 7 years. A benefit of this DSY reformulation is that it can be extended to test for more extreme weather, by selecting a reference year with a longer return period, and future conditions when applied to morphed future weather data. The reformulated DSYs still however only use air temperature, and so to address the issue of human heat stress, which is one of the focus areas of this thesis, an appropriate temperature metric is required that incorporates the other weather variables: solar temperature, humidity and wind.

The idea of taking a 1 in 7 year event as it stands is simplistic, since each year is an equally likely event, and the likelihood of extremes in the mean temperature is low. It is therefore necessary to apply a distribution estimate to the data, such that extreme values are not overlooked [135]. The General Extreme Value (GEV) distribution, which is frequently used for modelling climate change effects [136] is able to describe the statistics of extreme values, and is therefore well-suited to estimating the return periods of extreme events. The probability density function (PDF) is given by the GEV distribution, and the events (extreme and non-extreme) are fitted using a maximum likelihood estimation function. The GEV function is built into *MATLAB* and can be readily employed by fitting the distribution to the sum of the metric used in establishing the probabilistic return periods.

5.3.2 The redevelopment of the DSY

The original DSY reference weather data represented the third hottest year per region between 1983-2004. The redevelopment of regional DSYs starts by identifying that the baseline weather data is given over a 21-year period, and so the new DSY can simply be given as a 1 in 7 year ‘return period’. The DSY classification of ‘third hottest year’ just takes into account outdoor running-mean air temperature. However, overheating in buildings is defined by the experience of thermal discomfort by its occupants, such that the internal temperature feels too high to be comfortable. For the internal environment this can be calculated using **Equation 5-5**, and $T_{running\text{-}mean}$ can be calculated using **Equation 3-2** from CIBSE TM52 [72].

$$T_{comfort} = 0.33T_{running-mean} + 18.8$$

Equation 5-5

One of the simplest overheating metrics can be described as the number of hours over which temperatures exceed a static threshold, or put another way, the number of hours where forced cooling would be required; cooling degree hours (CDH). However, such a metric does not take into account severity, thus it would make no difference if the threshold were exceeded by 0.1˚C or by 10˚C, which is clearly incorrect. A simple weighting factor can be incorporated to rectify this shortcoming, and so the metric used in CIBSE TM49 for the new London DSYs is the weighted cooling degree hours (WCDH), shown in **Equation 5-6** and **Equation 5-7**.

$$WCDH = \sum_{all\ hours} \Delta T^2$$

Equation 5-6

where

$$\Delta T = T_{operative} - T_{comfort}$$

Equation 5-7

where $T_{operative}$ can be found from **Equation 4-3**.

CDH is a base definition of degree hours. WCDH (weighted cooling degree hours) can account for severity, since the ΔT^2 places a greater weighting on larger departures from the threshold temperature. Using this metric enables a more appropriate ranking of the 'hottest years' for DSY classification and is used in the DSY reformulation paper [137]. This method will also be used to create the UTCI-DSYs for heat stress assessment. To distinguish between near-extreme and extreme weather, DSYs have a return period of 1 in 7 years and 1 in 21 years respectively. This methodology was then replicated for the morphed future weather to create DSYs and UTCI-DSYs for 2030s, 2050s and 2080s.

5.3.3 Developing the UTCI-DSY

The task of performing a full assessment of overheating in buildings should be grounded in the thermal impact on people. The factors which cause people heat stress in the internal environment are sustained high temperatures, such as those found in a heat wave, and the combined effect of several weather variables, in particular air temperature, the solar radiative temperature, air flow and humidity. Given that people spend an average of >80% of their time indoors [138], the consequent internal environment in buildings during extreme weather conditions should form part of the overheating criteria in building assessments. The UTCI appears to perform better at forecasting public health risk, which is probably the most important consideration in building overheating. Going forward reference weather data for the building industry could include this aggregated equivalent temperature 'UTCI', which is a more appropriate index for assessing overheating conditions that result in heat stress.

Arguably a full thermal assessment in building simulations requires accurate and appropriate reference weather data. Reference data could provide broader capability for building models to test for near-extreme and extreme weather conditions, for general overheating (DSYs) and heat stress assessment (UTCI-DSYs), and for current and future climates. An analysis of both Met Office and UTCI heat wave growth trends will also be conducted in this thesis to ascertain the frequency of extreme hot weather to which buildings will be exposed and aid the development of a more complete health risk profile.

5.3.4 Establishing new reference weather data

Using the methods outlined above, a suite of UTCI-DSY reference years have been created for use in heat stress assessment for current and future climates, and in near-extreme and extreme weather, presented in the following tables. Applying the WCDH metric to current and historic weather data gives the ten calendar years with the longest return periods, from which the near-extreme DSY (1 in 7 year return period) and extreme DSY (1 in 21 year return period) can be selected. Taking London for example in current weather (see **Table 5-1**), the near-extreme DSY can be found by selecting the year with the closest to a 1 in 7 year return period, which is 1989 for air temperature and also 1989, but with a slightly higher return period, for UTCI temperature.

Table 5-1: Return periods of the ten calendar years for London with the longest return periods for air temperature and UTCI temperature.

Year	Tair return period (WCDH)	Year	UTCI return period (WCDH)
1975	5.1	1975	3.3
1983	5.4	1983	5.5
2013	5.9	2013	5.5
2005	6.5	2005	6.2
1989	**6.8**	**1989**	**7.4**
1990	12.5	1990	12.0
1995	14.8	1995	18.3
2003	15.5	2003	20.1
2006	16.0	2006	25.3
1976	22.2	1976	46.6

For current near-extreme weather conditions (with 1 in 7 year return periods), DSYs and UTCI-DSYs using the new methodology are shown in **Table 5-2** for all 14 UK locations, whilst return periods for extreme weather conditions are shown in **Table 5-3**. Overheating is generally not triggered in Belfast and Edinburgh. In these locations the GEV distribution is dominated by too many years with no incidences to fit a near-extreme return period, and so no values were returned. With the exception of London and Swindon, all other locations would use a different weather reference year for their respective UTCI-DSYs as opposed to the standard DSY. This is an important finding as it could have an impact on the way thermal performance is treated by the building industry. For instance, if the UTCI metric were adopted for overheating testing, especially for buildings housing vulnerable occupants, where heat stress is likely to cause illnesses and serious health risks, building designers would need to use a different reference weather year in thermal performance simulations. Similarly for testing thermal performance of buildings with the UTCI metric in extreme weather, potentially looking at the impact of heat wave type weather, the selected reference weather years for each location would also be different to those based on air temperature (**Table 5-2**).

Table 5-2: Return periods, selected year and the number of WCDH for near-extreme weather years for all locations using air temperature and UTCI temperature

Location	Air Temperature			UTCI		
	Year	Return Period	WCDH	Year	Return Period	WCDH
Belfast	-	-	-	1970	6.6	620
Birmingham	2005	6.7	809	1975	7.1	3040
Cardiff	1989	6.3	205	2013	5.4	1390

Edinburgh	-	-	-	1982	7.0	779
Glasgow	1983	7.1	316	1977	7.0	1079
Leeds	2000	6.5	591	2013	6.8	2126
London	1989	6.8	1816	2013	6.9	4426
Manchester	1983	8.2	511	1970	7.4	1929
Newcastle	1975	7.4	164	1997	6.9	790
Norwich	1996	5.3	837	1989	7.4	3643
Nottingham	2003	6.1	706	1970	6.7	2972
Plymouth	1983	7.8	248	2006	6.7	1341
Southampton	1989	7.4	650	1975	6.3	3245
Swindon	1989	7.2	1042	2005	6.5	2793

Table 5-3: Return periods, selected year and the number of WCDH for extreme weather years for all locations using air temperature and UTCI temperature

Location	Air Temperature			UTCI		
	Year	Return Period	WCDH	Year	Return Period	WCDH
Belfast	-	-	-	1995	16.7	1224
Birmingham	1976	19.6	2105	2006	26.4	5587

Cardiff	1990	22.0	759	2003	20.9	2773
Edinburgh	-	-	-	2006	16.6	1488
Glasgow	1995	8.4	459	1995	17.5	1774
Leeds	1990	16.5	1364	2006	21.0	2958
London	1976	22.2	3530	1995	21.1	6679
Manchester	1976	22.8	1280	1976	22.6	3135
Newcastle	1990	17.6	517	1990	15.0	1128
Norwich	1995	21.9	1519	1975	21.8	4693
Nottingham	1995	21.1	2023	1975	20.3	4955
Plymouth	1976	11.1	532	2003	24.0	3259
Southampton	1995	24.3	2067	1995	20.1	6693
Swindon	1995	19.5	2328	1995	19.9	4904

5.3.5 Creating new reference years for future climates

For the creation of future reference weather years, focus is returned to the three locations chosen in chapter 4 representing a good UK geographical spread: London, Birmingham and Plymouth. The morphed DSYs and UTCI-DSYs for near-extreme weather conditions in a probabilistic 2080s future climate are shown in **Table 5-4**. The morphed DSYs and UTCI-DSYs for extreme weather conditions (1 in 21 year return periods) for the 2080 climate are shown in **Table 5-5**.

Table 5-4: Future near-extreme DSY return periods

	Future Near-Extreme (2080s morphed)					
	Air DSY (overheating)			UTCI-DSY (heat stress)		
Location	Year	Return	WCDH	Year	Return	WCDH
London	1985	6.5	13399	1989	7.3	17214
Birmingham	1989	6.8	7568	1989	7.0	14860
Plymouth	1984	6.0	2422	1990	6.9	2963

Table 5-5: Future extreme DSY return periods

	Future Extreme (2080s morphed)					
	Air DSY (overheating)			UTCI-DSY (heat stress)		
Location	Year	Return	WCDH	Year	Return	WCDH
London	1986	20.7	18876	1995	20.8	22009
Birmingham	1995	20.2	12626	2006	18.5	20701
Plymouth	1995	19.6	4760	2003	15.3	5077

For each of the 10,000 morphed weather scenarios a near-extreme and extreme DSY and UTCI-DSY was generated. Selecting the DSY and UTCI-DSY year was done by taking the modal year from the 10,000 years for each location. The WCDH value for that year was then calculated as the mean WCDH value for that modal DSY / UTCI-DSY year. The impact of morphing has actually changed the year that would be selected, and is not just the current year morphed. Changing the metric has also changed the year, both in respect to comparing the air temperature DSY with the UTCI-DSY, and in respect to the historic DSY version. These findings are an interesting feature of the change in climate.

The predicted growth in Weighted Cooling Degree Hours (WCDH) for buildings for 2000s, 2030s, 2050s, 2080s for air temperature is shown in **Figure 5-5** and for UTCI temperature in **Figure 5-6**.

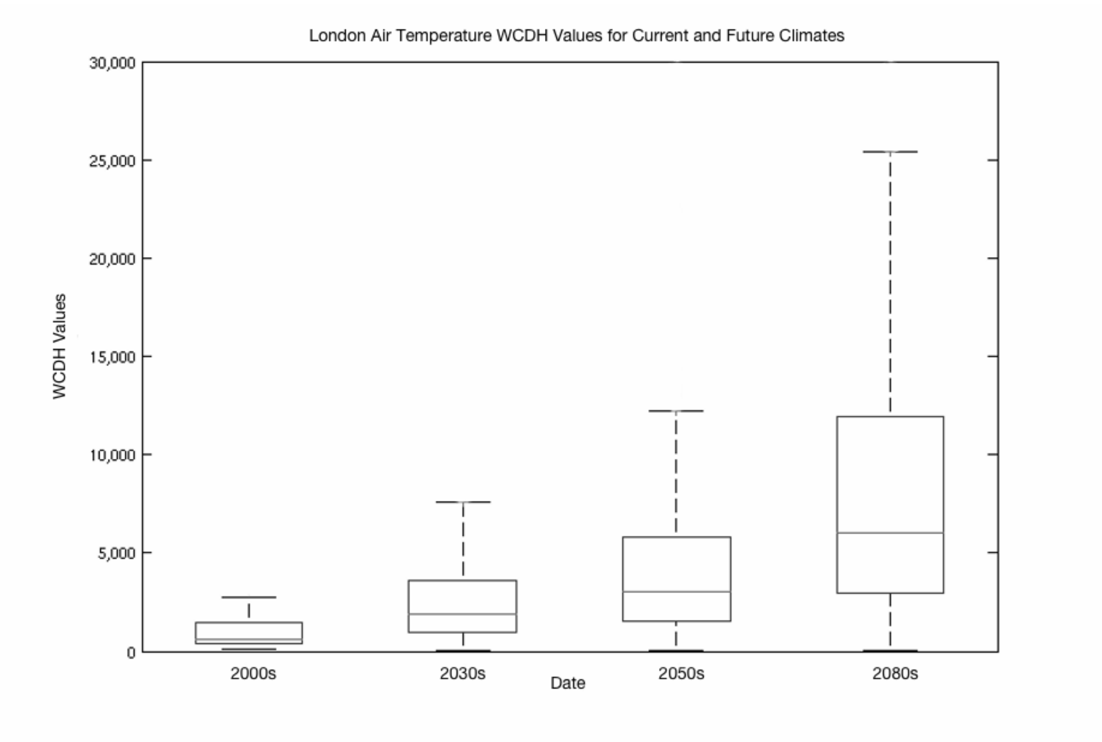

Figure 5-5: Predicted growth in London air temperature WCDH values for 2000s, 2030s, 2050s, 2080s

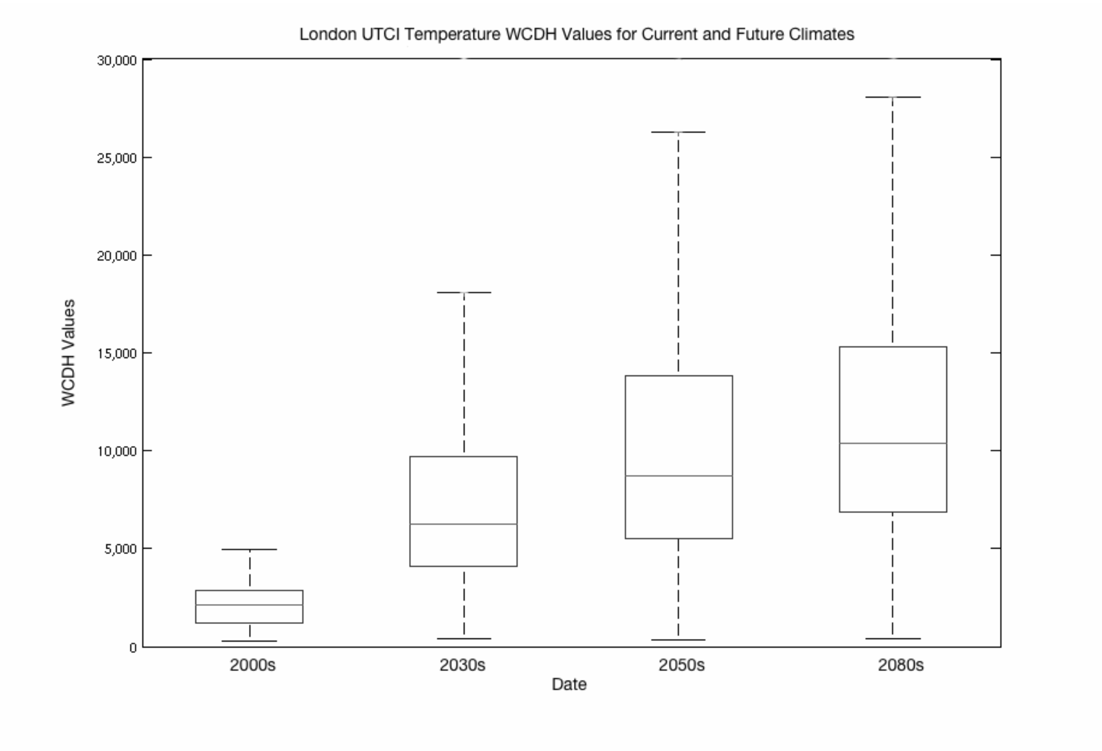

Figure 5-6: Predicted growth in London UTCI temperature WCDH values for 2000s, 2030s, 2050s, 2080s

Building on the new DSY reformulation methodology, this thesis has further developed reference weather data for the built environment industry by introducing the UTCI-DSY, which adds extra environmental parameters that affect the thermal sensation of the human body. This work has focussed on three developments in particular to create a suite of reference years that can be used in the following scenarios:

- Heat stress overheating assessment
- Extreme weather
- Future climates

5.3.6 Analysing the new weather reference years

The calendar years for both air temperature and UTCI temperature shown in **Table 5-1** followed the same ten spot ranking. In both cases results confirm the near-extreme reference year (the standard DSY with a 1 in 7 year return period) should remain unchanged from current CIBSE guidelines as 1989. However, for extreme weather (1 in 21 year return period), the 'extreme DSY' becomes 1976 if using air temperature for general overheating, meanwhile the 'extreme UTCI-DSY' becomes 2003. Both years are recognised as two of the hottest years on record, yet interestingly 2003 was the year of the extreme heat wave that caused around 50,000 deaths across Europe [53]. By selecting 2003 as the 'extreme UTCI-DSY', engineers would be testing their building designs against hot weather conditions that are known to cause human heat stress and serious health risks.

The set of DSYs shown in **Table 5-4** and **Table 5-5** show the years selected for general overheating DSYs and heat stress UTCI-DSYs in near-extreme and extreme weather scenarios. UTCI-DSYs give greater overheating in general, which is to be expected since they are specifically addressing heat stress weather scenarios. In principle, results from the work presented in this thesis indicate that the reformulated DSYs are adequate for use in overheating tests for standard use buildings, whilst UTCI-DSYs could be used for assessing buildings housing vulnerable inhabitants such as hospitals, schools or care homes, since the UTCI metric is better tuned for human heat stress.

Analysing the WCDH values shows that the current near-extreme London DSY (1 in 7 year return period) has a WCDH value of 1,816 rising to 13,339 by 2080 – an increase factor of 7.3, indicating longer and more severe periods of overheating. For the extreme London DSY (1 in 21 year return period) WCDH values rise from 3,530 to 18,876; an increase of a factor of 5.3. The figures for the UTCI-DSY years show a larger increase over time with the current near-extreme London DSY holding a WCDH value of 3,930, rising to a possible 17,214 by 2080 (an increase of a factor of 4.4). For the extreme UTCI-DSY, the current WCDH value of 5,657 could rise to 22,009 (an increase of a factor of 3.9). Results illustrated in **Figure 5-6** show the projected growth of the UTCI temperature WCDH percentile values from current to future climates. The current WCDH value representing an extreme UTCI-DSY weather year in London is 5,657. From **Figure 5-6** it can be seen that the 50th percentile point of the 2080 WCDH value exceeds 10,000. This indicates that the kind of hot weather described by the current extreme UTCI-DSY, could possibly become at least normal by 2080. Attention should briefly be drawn to the current extreme DSY for Plymouth; the results are shown in brackets, since the return period of 10.7 years is clearly too far from the 1 in 21 year return period needed to define an extreme year, and this result must be discounted. Results show a slight disparity between the growth curve of air temperature based WCDH compared to UTCI-based WCDH, and this could be explored in further studies. However, what can be concluded is the importance of choosing the appropriate DSY and overheating metric for the given building assessment.

5.4 Chapter summary

This concludes the chapter on future indoor conditions and reference weather years. Future hot days and heat waves have been analysed using Met Office air temperature thresholds and UTCI 97.5th percentile thresholds, and growth trends and frequency forecasts have been predicted. New UTCI-DSYs, appropriate for the assessment of human heat stress levels in buildings have also been established. The suite of UTCI-DSYs are particularly relevant for thermally assessing buildings that accommodate vulnerable occupants, and can be used in near-extreme and extreme conditions, for current and future climates. The next chapter will investigate the localised internal heat stress within a building using computational fluid dynamics and the UTCI metric. A surrogate model will be developed to rapidly calculate internal heat stress levels for current and future climates.

6 Analysing indoor heat stress for current and future climates

6.1 CFD and building modelling

As expedient as bulk building models are, such as those described at the beginning of chapter 4, the question of what happens locally within the indoor space, and particularly what heat stresses are occurring on a human body, cannot be answered using this bulk model approach. In order to understand the heat stresses on a human body, it is necessary to look inside the indoor space. A technique that gives a finer analysis is computation fluid dynamics (CFD), which offers a detailed view of all the above parameters within the space itself. Using CFD provides localised values for environmental parameters for a fuller picture of the heat stress index, provided the input data is of sufficient quality. The human bodily thermal sensation is affected by a combination of environmental variables, which contribute to an equivalent temperature that people feel, and all need accounting for to fully represent thermal effects on the human body. The UTCI specifically accounts for air temperature, humidity, solar radiation and air flow (or wind), providing a complete human heat stress metric in degrees centigrade [56], [61]. The main difference between the UTCI and indices such as PMV is that PMV is a non-thermal index with discrete outputs that gives a subjective comfort value rather than a continuous linear temperature value, and PMV deals particularly with comfort rather than heat stress. The advantage of using PMV is that it is possible to factor human activity within the building to assess comfort, giving a contextual parameter to building use (for instance, if the building were a gym or a manual labour factory rather or an office, then clothing and metabolic activity would be quite different, and comfort levels would be different). In this thesis the focus is on finding the internal building response temperature to the external weather parameters using a finely graduated, continuous index rather than discrete value on a 7-point scale. The UTCI provides the response temperature in ˚C, and accounts for what the inhabitant is wearing based on wind speed [55].

It is well understood that localised internal environmental parameters affect how the human body feels thermally, yet it is common practice for thermal comfort assessments in the design of habitable spaces to use bulk models for determining overheating levels in indoor environments. This is mainly borne of the need to simplify construction design processes, since fluid flow and heat transfer modelling (CFD) can be a lengthy and expensive exercise, and a simple bulk analysis for building zones can give a reasonable thermal account of an indoor space. Yet CFD simulations can provide the kind of localised detail that enables more accurate thermal comfort assessments by outputting a full description of the localised internal conditions. In the building design industry this will become more important as the climate changes and the requirement to engineer adaptable buildings gathers momentum, whilst in the automotive and aviation industry it is arguably an immediate interest, given that in such internal environments thermal comfort can be more controlled [139], [140]. The following sections contain a background of CFD and its use in buildings.

6.1.1 Fundamentals of CFD

The basis for all computational fluid dynamics is the set of Navier-Stokes equations for describing the flow of a viscous fluid, which represent the conservation of mass and momentum in the fluid. For a compressible fluid, the law of conservation of mass can be expressed in the form of the mass continuity equation **Equation 6-1**:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u}) = 0$$

Equation 6-1

If the fluid is incompressible, i.e. the density ρ is constant, then this can be simplified as **Equation 6-2**:

$$\nabla.\boldsymbol{u} = 0$$

Equation 6-2

The conservation of momentum represents the application of Newton's second law of motion to a fluid including viscous and pressure terms and can be written as **Equation 6-3**:

$$\rho \frac{Du_i}{Dt} = -\nabla p + \rho \boldsymbol{g} + (\mu \nabla^2 \boldsymbol{u})$$

Equation 6-3

The conservation of energy equation represents the application of the first law of thermodynamics. The conservation of energy in relation to fluid dynamics can be described as such: the rate of change of energy inside the fluid element is equal to the net flux of energy into the element plus the rate of work done on the element due to body and surface forces.

$$\rho \frac{De}{Dt} = \rho \frac{\partial e}{\partial t} + \rho \nabla \cdot \left(e\vec{\boldsymbol{V}} \right)$$

Equation 6-4

6.1.2 Background to the habitable environment

In order to drive a building design software package it is necessary to provide a reference weather file such as the TRY or DSY containing weather parameter values. It is also necessary to provide a building design, typically as a CAD file. These elements are sufficient for providing surface temperatures that can be used as input boundary conditions to model heat and fluid flow inside a building, using a CFD software package. This can and has been used to analyse the internal environment for specific boundary conditions [104], [141]–[143].

6.1.3 Considerations for using CFD in building design

Buildings are difficult to design because they have so many parameters and variables. For instance resizing a window can make the difference between a building passing a thermal comfort test or not passing. If the analysis is done with CFD, then adjusting parameters slightly in a design tweak can end up costing a designer weeks in computer time to re-run the CFD a task. It would be better to create an emulator model that could simulate the results of a CFD run. To do this requires many actual CFD runs in order to create the emulator in the first place, so it is not without its difficulty, however when the emulator is created, it is then possible to emulate CFD outputs within seconds for that building, rather than weeks of running another CFD a simulation. In this thesis a surrogate model is created to emulate the CFD outputs for thermal comfort in a standard office room. Variables were chosen for temperature at the boundary conditions, air speed flux in and humidity. I show that it is possible to get within 1% of the actual CFD result using the emulator, and suggest that this method in its current form could be applied to large building projects that warrant the time spent creating the emulator in the first place, but that lessons could be learnt in creating faster CFD training sets for next generation emulators in the future.

6.1.4 Turbulence and buoyancy

For CFD simulation of built environment cases there are two further issues to be considered; the presence of turbulence, and the modelling of thermal buoyancy. Thermal flows are partly (or sometimes, wholly) driven by buoyancy effects caused by differences in density related to temperature differences in disparate parts of the flow. For large contrasts in temperature, the effects of variable density have to be considered directly through the use of a compressible solver; for lower temperature differences, as here, buoyancy can be simulated through the commonly-used Boussinesq approach, in which the air is considered incompressible but a temperature-dependent body force included in the momentum equation to force the convection. Turbulence is a complex state of fluid flow characterised by random motions over a range of length scales. For buoyancy-driven flow in a room as considered here, typical Reynolds numbers for the flow are in the range $\gtrsim 1\times10^5$ and therefore the presence of turbulence has to be accounted for [143]. Including turbulence modelling in the simulations for this thesis means that the Navier-Stokes equations for velocity and pressure in fluid flow have to be treated as having both mean and fluctuating parts to the flow; what this entails after averaging the equations is the inclusion of a Reynolds stress term for the fluctuating flow and a Reynolds-averaged Navier Stokes (RANS) equation to govern the mean flow. However, the Reynolds stress term, which can be likened to stresses in other materials, deals with the viscosity and density of the fluid and cannot be reconciled with the RANS equations for velocity and pressure. To solve this, Boussinesq introduced the idea of eddy viscosity, which he proposed could relate the turbulence stress to the mean flow velocity. By including an eddy viscosity term, the equations for mean flow and turbulent flow could be solved. The eddy viscosity model (EVM) is shown in **Equation 6-5**.

$$-\overline{v_i'v_i'} = v_t\left(\frac{\partial \overline{v_\iota}}{\partial x_j} + \frac{\partial \overline{v_\iota}}{\partial x_j} - \frac{2}{3}\frac{\partial \overline{v_\iota}}{\partial x_j}\partial_{ij}\right) - \frac{2}{3}K\partial_{ij}$$

Equation 6-5

As a basic user of *OpenFOAM*, and since turbulence modelling often uses the RANS approach for the reasons given above and in other literature [144], I have used the RANS model and the standard $k\epsilon$ model, also following common practice [144]. The $k\epsilon$ model represents the effects of the turbulence by solving for two statistical parameters, the turbulent kinetic energy k and dissipation ϵ. More advanced models are not necessary for built environment cases since the time scales over which steady state solutions are achieved are relatively long in comparison to the turbulence time scales. The transport equations for these variables are shown in **Equation 6-6** and **Equation 6-7**.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k$$

Equation 6-6

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(P_k + C_{3\epsilon}P_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon$$

Equation 6-7

Aside from the constants, the key terms are turbulent viscosity μ_t and the buoyancy term P_b, which itself is governed by the Prandtl number and the coefficient of thermal expansion.

In 3D building modelling CFD studies generally use the finite volume method (FVM) for heat transfer and fluid flow calculations, in which the integral form of the governing equations is used (**Equation 6-8**).

$$\frac{\delta}{\delta t}\iiint Q\, dV + \iint F\, dA = 0$$

Equation 6-8

Where Q is the vector of conserved variables, F is the vector of fluxes, V is the volume of the control volume element, and A is the surface area of the control volume element. Integral equations can be formulated of all the governing equations (continuity, momentum and the turbulence model equations) by integration over the volume of a single small volume of space referred to as a control volume or cell, providing a difference equation relating the change in the dependent variables in the cell to the fluxes across the cell boundary. Dividing the whole space of interest into *N* non-overlapping cells (forming a mesh) creates a set of *N* simultaneous equations which can then be solved through matrix inversion to advance the solution through one computational step.

6.1.5 Surrogate modelling

Running a CFD analysis for every design iteration is far too computationally costly even for a single set of weather conditions, let alone for dynamic combinations of weather parameters and building surface temperatures. The objective of the current work is to demonstrate the construction of a simplified ‘surrogate' model from a limited number of CFD calculations which can then be used to explore the internal environment for a wide range of possible boundary conditions.

Surrogate modelling, or emulation, has generally been driven by a need for expediency in generating results for real-world applications. It is employed when an outcome of an experiment or another model is difficult to obtain or process, and when large numbers of outcomes are required [145]. Computational surrogate modelling was primarily developed in the late 1990s, though the theory predates this, and generally surrogate model construction methods involve statistical regression. There are various techniques for doing this, though they broadly follow the same methodology, namely to take empirical data or results from another model, and to use that data as a set of fixed points with which to train a new model. This new surrogate model should be capable of emulating the output of the original model as closely as possible for any values of the initial parameters that were used to create the training data points.

There are several techniques for creating surrogate models such as polynomial regression [146] Random Forest (RF) method [147], MARS [148], Support Vector Machines (SVMs) [149], Artificial Neural Networks (ANNs) [150] and Gaussian Process Emulation (GPE) methods [151]. The most frequently used, and best performing surrogate modelling technique is the Gaussian process emulator [145], [152], also called the Kriging model [153]. The Kriging process is widely used as it gives both a mean fit to the data being modelled together with an estimate of the expected variance for untested output combinations, and is relatively computationally cheap to construct [154], and for these reasons this GPE/Kriging method will used to create the surrogate model. This thesis seeks to overcome both the issues of full thermal comfort assessment and the computational cost barrier to using CFD for this purpose by implementing surrogate modelling at the building design stage.

6.2 Methods for simulating fluid flow in buildings

6.2.1 Developing the CFD and surrogate modelling process

The following section describes a method of creating a surrogate model to emulate full CFD simulations of thermal stress within a habitable space. By simulating heat and fluid transfer of the environmental parameters using Computational Fluid Dynamics, and creating a surrogate model that could emulate the results of these CFD simulations, a rapid human heat stress analysis can be provided for any given environment. In the end, the surrogate model should be able to emulate the internal heat stress within the building and therefore be capable of utilising standard building design software output values for any weather (current and future) and for any location and rapidly return the heat stress results of a steady state fluid flow and heat transfer simulation. In essence the surrogate model is being trained to return, as accurately as possible, the same results of a single output from a CFD simulation. To carry out this work the following ten-step process was used:

1. Create the building model
2. Set up the CFD code and solver
3. Mesh the building model ready for CFD application
4. Create the boundary conditions for the model using building software
5. Run a separate CFD case for each of the boundary conditions
6. Process the CFD output and return the value needed for the emulator
7. Create the surrogate model and refine it

8. Validate the emulated model
9. Use parameters from future weather files to create surface conditions for the building in this thesis, using building design software
10. Use the surrogate model to translate the building surface conditions and external weather parameters to an internal equivalent temperature for human heat stress

6.2.2 Creating the building model

The building design (**Figure 6-1**) is a simple box room measuring 5x5m (width and depth) by 2.5m in height. It has one window centrally split with a bottom-up sliding design, like as a sash window, measuring 2m wide by 1m in height, allowing for the simulation of solar radiative effects. The room is simulated with direct sunlight, dampened by the glass in the window, incident on the floor. The elevated temperature caused by this solar thermal gain is averaged evenly over all the cells on the surface to provide a boundary condition, driving buoyant flow. The spatial variation is only accounted for in the temperature boundary condition of the floor and the building is modelled as though solar radiation is solely incident on the floor surface. Further work would include a solar ray path for radiant energy, dynamically changing the cell boundary conditions for the room surfaces, depending on where the rays intersect the walls, then solve with respect to the movement of the sun. The air inlet is 0.1m in height and the full width of the 2m window and is located at the bottom of the window – this models a slightly ajar window, as would be typical of window use in a naturally ventilated building. The air outlet is located at the top of the window, with the same dimensions as the inlet, and this would be typically found in a vented window design. Airflow is driven by external wind conditions. This simple building does not contain any furniture, other objects or contents that contribute to internal heat gains. This building could of course be adapted to include furniture, doors or other elements, but in this case the geometry simple for expediency. The building was created using the open-sourced CAD programme *OpenSCAD* and exported as a Stereoscopic Lithography (STL) file for meshing. The mesh was created using the *snappyHexMesh* tool found within the *OpenFOAM* library.

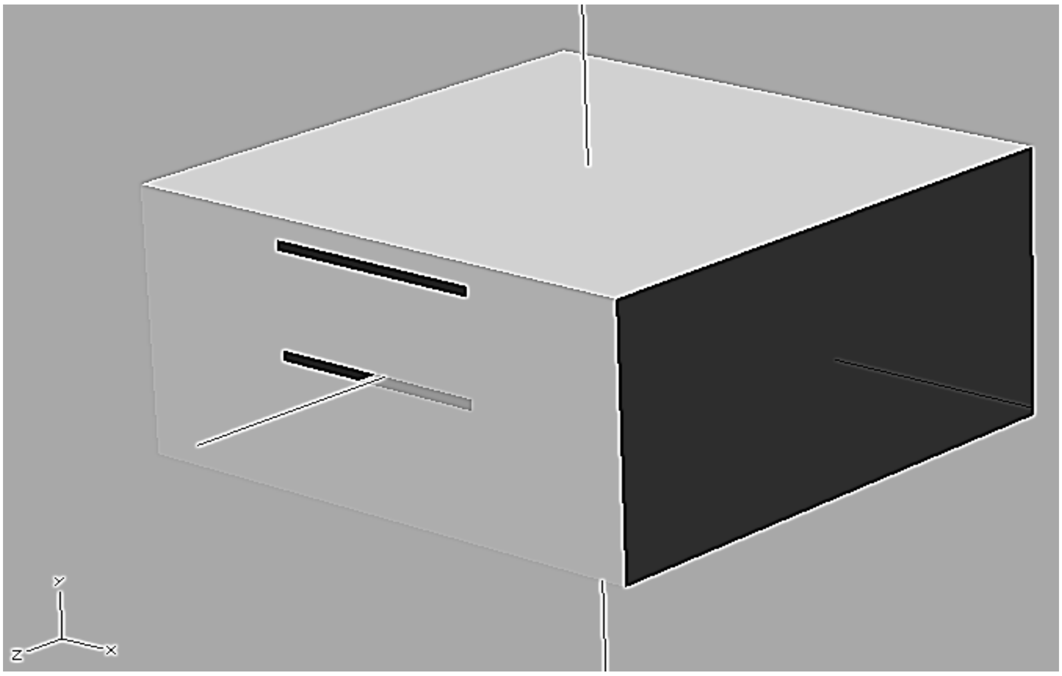

Figure 6-1: *OpenSCAD* graphic of building model, showing window inlet and outlet

6.2.3 Setting up the CFD model

The open-source CFD package *OpenFOAM v2.1* was used to conduct the CFD simulations as it is freely available and its code can be adapted to create new solvers and parameters. Air flow and heat transfer in this habitable space is buoyancy driven, and the adapted CFD solver used here is based on the *buoyantBoussinesqSimpleFoam* solver found in the *OpenFOAM* library, which uses the Boussinesq approximation for solving buoyancy driven flow. The pressure-linked *Simple* algorithm is used in this thesis since our CFD cases are steady-state. The pressure gradients in the CFD cases are relatively small, and so turbulence is solved using the $k\epsilon$ model.

Turbulence modelling was needed based on assessment of the average Reynolds number. For the naturally ventilated habitable space considered in this thesis average air inlet velocity is 1 to 5 ms^{-1}, the window has a length scale of 2m and the room has a length scale of 5m, resulting in an estimated Reynolds number of between 1×10^6 and 1×10^7. In this case $\Re \gtrsim 1\times10^5$ indicated a turbulent flow regime, and the standard $k\epsilon$ turbulence model was selected. The solver itself was not altered and its capabilities remain the same as the original, however it was extended to include weather parameters and the calculated UTCI heat stress parameter using functionObjects, UTCIEqn and makeUTCI files to link the UTCI function with the solver. As an index the UTCI has been shown to be an accurate measure of a person's physiological thermal sensation, and represents an appropriate way of gauging thermal comfort [57].

The adapted solver was validated by applying it to a known CFD case involving heat transfer and ventilation in an office room and comparing results [155]. The Loomans study was an investigation into using CFD to model ventilation based on laboratory collected data. The Loomans room case was recreated and the same boundary conditions were applied so that the adapted

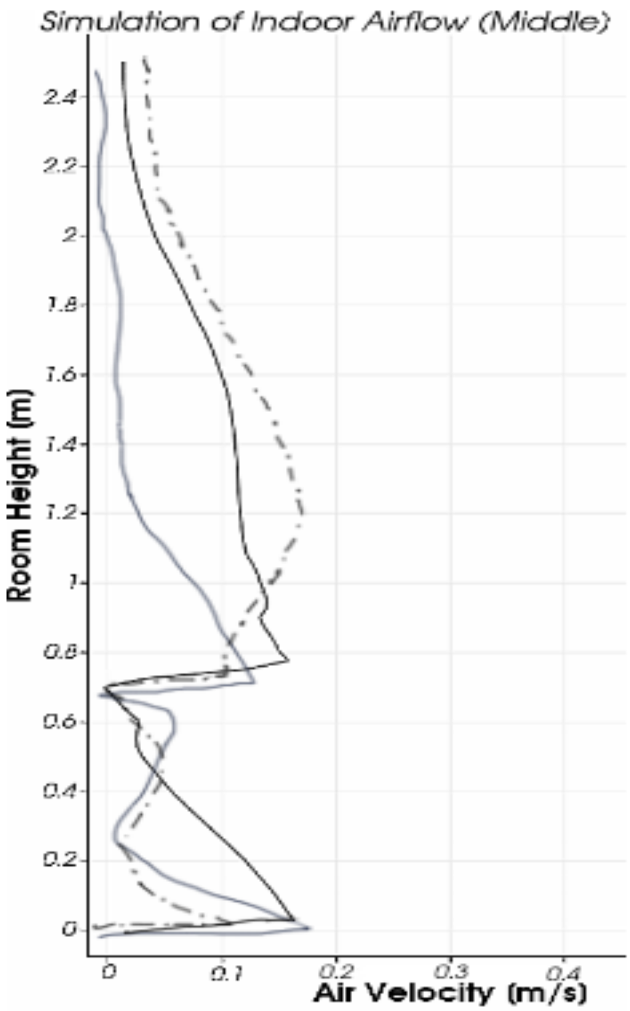

Figure 6-2: Airflow profile from the middle of the original Loomans building case. **KEY:** black line represents results from this thesis; grey line represents Loomans' simulated results; dashed line represents Loomans' experimental data.

solver could be tested. The results of this test indicated an airflow profile matching Loomans' original simulations, whilst better taking account the experimental data, especially in the room height region of 1 to 2m, which was to be expected given advancements in CFD over the intervening years (**Figure 6-2**). This validation confirmed the applicability and accuracy of our solver.

6.2.4 Constructing the geometry mesh

The building was meshed using 3 mesh sizes to find the most appropriate number of cells. Meshes with 1 million, 2.5 million and 5 million cells were created using the *blockMesh* utility in *OpenFOAM* and combining these with the STL files for the window vents created in *OpenSCAD*. The block mesh and STL window files were combined into single meshes using the *snappyHexMesh* tool, also available in the *OpenFOAM* release. The mesh with 1 million cells contained areas around the window vents with high non-orthogonality, whilst this was not the case with the higher resolution meshes. The 5 million cell mesh and the 2.5 million cell mesh gave broadly similar results and so the 2.5 million cell mesh was chosen for its shorter run times and faster convergence.

6.2.5 Setting boundary conditions for the CFD cases

In total five parameters with value ranges were chosen from outputs of a typical building model application, including humidity, air speed (wind), air temperature and internal building surface temperatures (**Table 6-1**). These parameters would provide the boundary conditions for the CFD model. A more detailed model would treat each surface temperature as a separate parameter, however the building model was simplified in this thesis by treating the floor as the surface receiving full incident solar radiation, and ignoring diffuse solar radiation that may affect other surfaces. This simplification was done to avoid excessive numbers of variables, which would in turn require a much larger number of CFD simulations for constructing an emulated model, and would affect the quality of the emulator. Once the parameters were chosen, the range of values for each variable were selected based on the validity conditions specified by the UTCI code documentation. This ensured that the UTCI temperature calculations in the CFD simulations would be valid. The temperature range was chosen so that building's thermal response could potentially be tested in cold weather, since the UTCI metric can accommodate both heat and cold stress testing. The air speed is the external wind speed which is arriving perpendicular to the window. The window is modelled as slightly ajar to allow for an airflow at the inlet, and so the air speed through the inlet in the window is equivalent (at the boundary) to the external wind speed. At the outlet the air speed boundary condition was initialized at 0 ms^{-1}, which not the case in reality, but is acceptable for buoyancy driven simulations. Ensuring better emulator accuracy could have been achieved by selecting narrower value ranges for each parameter, however the ranges must accommodate all possible hitherto unknown weather variable combinations for the future, so the humidity range could have been bounded at 10% to 90%, but that range would expose the model to the possibility of crashing if any weather parameter value outside that range was input. I deemed the potential slight gains to be had were not worth the risk of a limited model.

Table 6-1: Weather parameters and value ranges for input into the CFD building model

Variable	**Range**
External air temperature	-12˚C to 58˚C
Wall temperature	-12˚C to 58˚C

Floor temperature	-12˚C to 58˚C
Air speed (wind)	0-5 ms^{-1}
Humidity	0-100%

The emulator requires ten outputs per variable for an accurate model to be constructed. With five parameters, a total of at least 50 CFD runs with different boundary conditions are required in order to gain 50 outputs. Selecting the 50 different sets of boundary conditions was performed using a Latin-Hypercube sampling technique, which ensures well-spaced parameter selection. By using a sample of boundary conditions taken from various weather conditions and running these as separate CFD cases on the same building model, the average internal heat stress temperature for the building for a wide range of weather conditions could be found. This was achieved by taking the cell-weighted average value over all cells in the mesh.

6.2.6 Running the CFD building model cases

Once the boundary conditions were generated and the desired output chosen, this information was used to create and run the CFD cases and solved using the custom buoyancy solver. The calculations were performed on a linux-based 64 core machine with and 128GB RAM, and with each of the 'fat' nodes running on quad Intel Xeon E5-4620 processors. 1 core was utilised per CFD case, thus each of the cases were run simultaneously. CFD simulations are solved iteratively and the solution is achieved once the value of the solution has converged to within a defined variance from the previous iteration: the convergence criteria. The convergence criteria for the cases were set to 1×10^{-5} and each individual CFD simulation took between 300-800 hours to converge.

A graphic of the air velocity glyphs and temperature ranges from one of the CFD runs is shown in **Figure 6-3**. Glyphs simply represent vectors, but are represented visually by size according to the magnitude of the vector (i.e. a visually large glyph for air velocity would have a larger velocity than a visually small glyph) It is possible to see the inlet airflow and outlet vent, as well as some of the flow characteristics toward the back of the building.

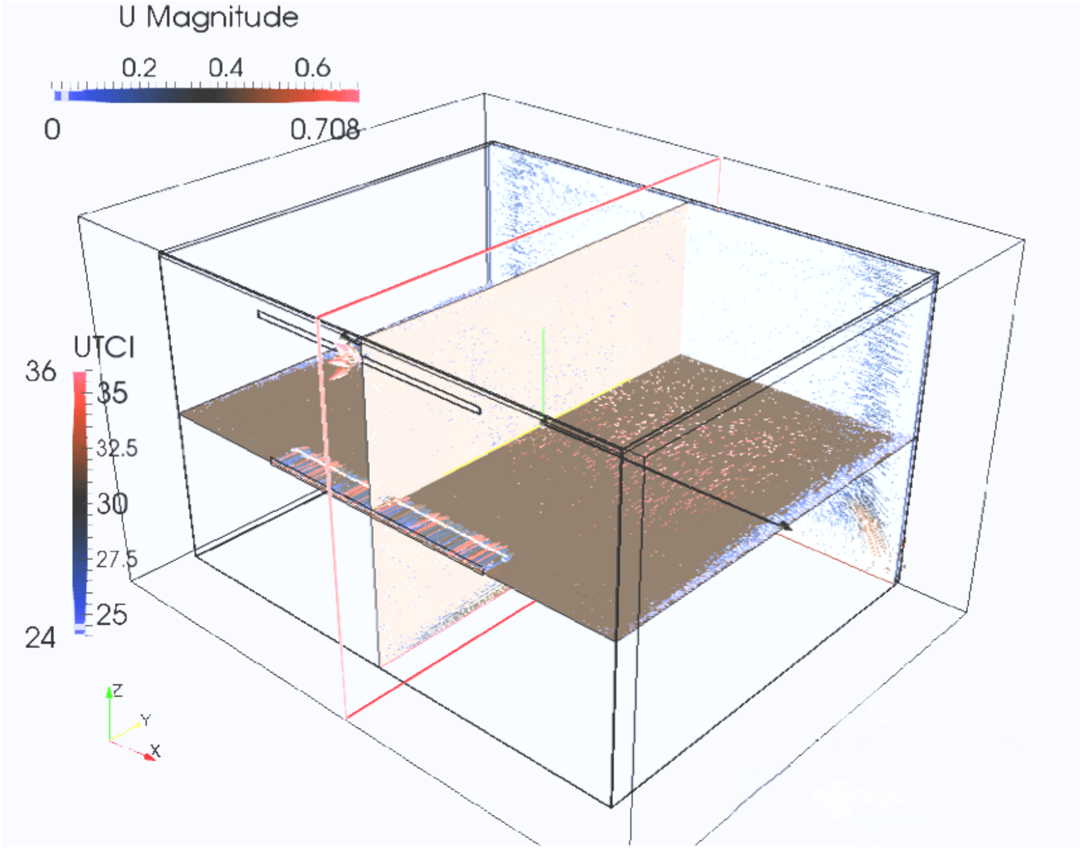

Figure 6-3: Airflow and UTCI temperature distribution within the building model

6.3 Creating the surrogate model

6.3.1 The need for surrogate modelling

Buildings are difficult to design because they have so many parameters and variables. For instance resizing a window can make the difference between a building passing a thermal comfort test or not passing. If the analysis is done with CFD, then adjusting parameters slightly in a design tweak can end up costing a designer weeks in computer time to re-run the CFD task. It is therefore sensible to create a surrogate model to emulate CFD results. Once the surrogate model is created it is possible to emulate CFD outputs for that building within seconds. In this model the reference building is a single geometry and the weather parameters make up the input variables. An extension of the thesis would be to model the input weather conditions on multiple building geometries, which would include variable window sizing.

6.3.2 Design of experiments

Selecting an appropriate output from the CFD results to use in the surrogate model construction process requires careful consideration. The construction process requires a well-distributed range of input values and it is therefore important that the input space is sampled as efficiently as possible.

The most common method for creating the training set is to use a maxi-min Latin Hypercube. It has been shown though previous research that the size of the training set should be $10d$, where d is the number of input parameters [156]. Since the CFD model in this thesis has 5 parameter inputs, the R package *lhs* (Latin Hypercube Sampling package) was used to generate 50 input samples, ***D*** [157]. The CFD model was then executed for each of the scenarios in ***D*** to determine *f(**D**)* and used this data to create the emulator.
Gaussian Process Emulators provide an estimation of the simulator output $\hat{f}(x)$ for a given function, $f(x)$ (**Equation 6-9**) such that:

$$\hat{f}(x) = N\left(m(x), \sigma^2 c(x,x)\right)$$

Equation 6-9

Where $m(x)$ is the mean of *x* and $\sigma^2 c(x,x)$ is the covariance of *x* Modelling the output of the simulator in this way is useful because, for each of the unknown output (i.e. $\hat{f}(x)(x \notin \boldsymbol{D})$), the emulator provides a mean and variance for its predictions from the functions $m(x)$ and $\sigma^2 c(x,x)$ respectively. For points where $x \in \boldsymbol{D}$, the covariance function $c(x,x) = 0$ and $m(x) = f(\mathrm{x})$ and therefore $\hat{f}(\boldsymbol{D}) = \hat{f}(\boldsymbol{D})$).

The accuracy of the emulator outputs increases rapidly with only a few additional training points, and as a rule of thumb, an accurate emulator requires at least ten data points per parameter emulated. The emulators make estimations of smoothness of the curve. For multidimensional emulators, the smoothness is estimated by determining the ‘most-likely’ smoothness in each dimension. This estimation of smoothness is based on the data provided by the training points and is the most computationally expensive task involved in creating the emulator [158]–[160].

6.3.3 Defining the output of the simulations

Several outputs from the CFD simulation results were assessed for their suitability to create a working surrogate model. A discrete output was attempted by taking the ‘percentage of cells within the building whose UTCI value exceeded a given threshold temperature’ as an output. This resulted in a range of output values that did not follow a well-distributed continuous pattern and consequently produced a poor emulator. This can be seen in **Figure 6-4** where a significant number of outputs had zero values because the respective CFD simulations, with particular combinations of variables, produced no cells with UTCI temperatures that exceeded the threshold temperature. An effective surrogate model could not be produced from such a range of outputs. The output which gave a good distribution of continuous values was defined as the average UTCI temperature value taken over the whole cell array. This output provided a continuous range of values appropriate for constructing a surrogate model.

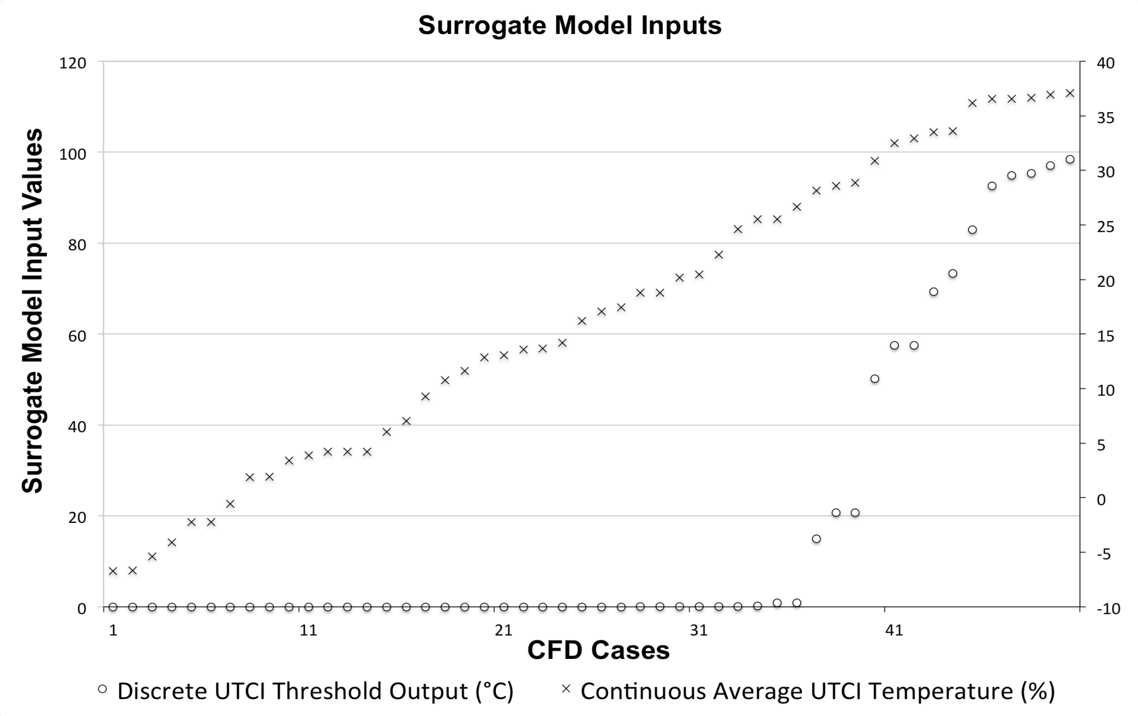

Figure 6-4: Distribution of discrete and continuous input values

6.3.4 Kriging

The surrogate model was created using the *km* function in *DiceKriging* [161] and *RStudio* [162]. The emulator uses the exponential structure for the correlation function (**Equation 6-10**):

$$c(x, x') = e^{\frac{-h}{\theta}}$$

Equation 6-10

where $h = |x - x'|$ and θ is the range parameter which controls the smoothness of the output in each of the d input dimensions. A linear trend was used for the mean function.

6.3.5 Validating the surrogate model

The surrogate model was cross-validated using the 'leave one out' principle [163]. Since there were 50 CFD cases, the first validation emulator was created using the results from cases 1:49 and validated against case 50. The second emulator was created using the results from cases 1:48 and case 50, then validated against the result of case 49, and so on… This method of validation is widely used in emulation research work and is a fast and effective technique. It also has the benefit of providing a full class of separate validation results. The results of this validation technique can be seen in **Figure 6-5**, which shows that all but two of the 50 emulated solutions resided within 95% confidence bands for each of the corresponding CFD simulations.

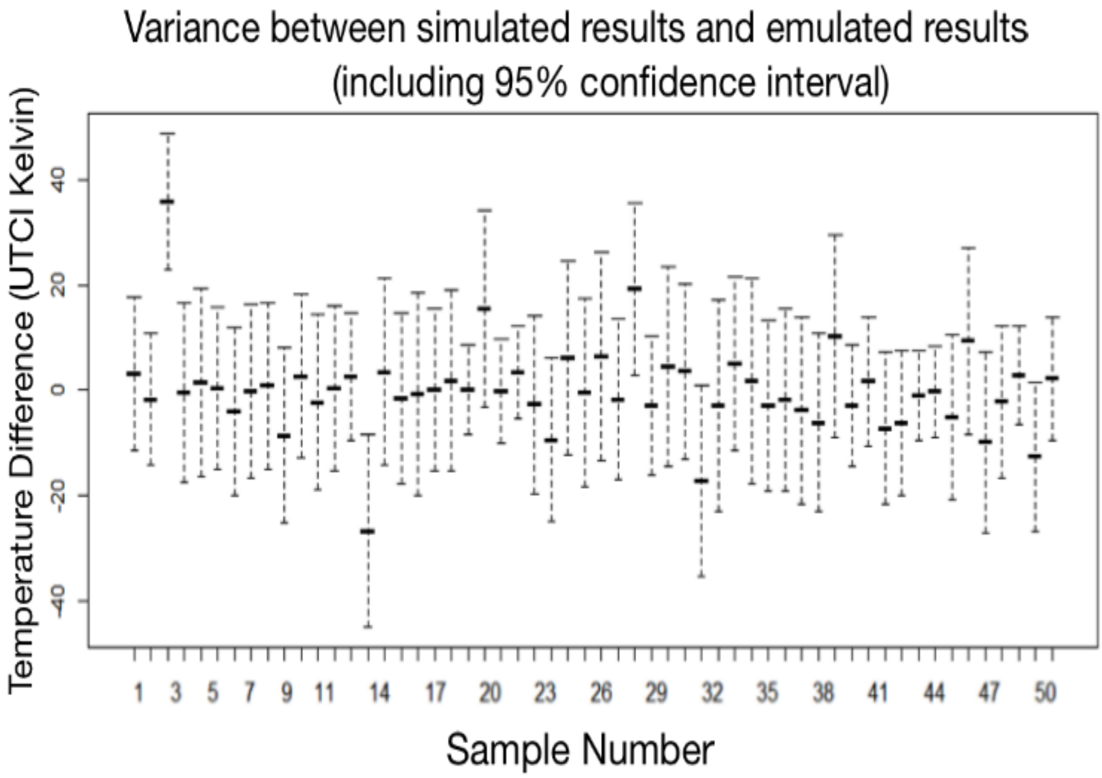

Figure 6-5: Cross-validation of the surrogate model using the 'leave one out' principle

6.3.6 Running the building design software

Typical reference weather files from current climates in three UK cities: London, Birmingham and Plymouth were selected for input into building design software to calculate surface temperatures, to use with the surrogate model for emulating the internal UTCI heat stress values. The building design software used is *EnergyPlus*, which is a well-used and long established open-source building energy package developed by the American government. The open-source package *OpenStudio*, used in conjunction with *SketchUp* was utilised in this thesis to run the building model for use in *EnergyPlus,* delivering output variables for humidity, wind speed and surface temperatures for each calendar day.

In an actual dynamic thermal model, windows would open and close more in response to changing internal conditions. For example, designing a rectangular window in *EnergyPlus* that is 1m^2 in area, with a 1ms^{-1} air speed gives a vent rate of 1m^3s^{-1}. A half open window of that size results in a vent rate is 0.5m^3s^{-1}, whilst the inlet air speed remains at 1ms^{-1}. It is not possible to account for this in CFD without dynamically changing the geometry during the simulation, which could be done using a dynamic mesh. However, this would still require coupling the dynamic mesh around the window with a threshold cell value to trigger a change in mesh geometry. In this simple buoyancy simulation for a reference building, the risk of destabilizing the convergence of the CFD simulations would have been high, resulting in failed solutions. The aim of this thesis was to construct an emulator that could test a single building geometry's response to any possible type of weather we might encounter in the future, not necessarily to model human behaviour that would include opening and closing windows. *EnergyPlus* was used to supply the boundary conditions for the building for the CFD runs, which required keeping the *EnergyPlus* building model static, and to the same specifications as the CFD mesh.

6.3.7 Analysing future internal heat stress

The *EnergyPlus* output values were input to the emulator, which produced an internal UTCI heat stress temperature value for each day. This process was then repeated using future reference weather data, morphed using the high emissions scenario [73], and results for the internal environment were generated from the surrogate model for three UK locations. Results for

Birmingham are shown in **Figure 6-6**, results for London are shown in **Figure 6-7** and results for Plymouth are shown in **Figure 6-8**.

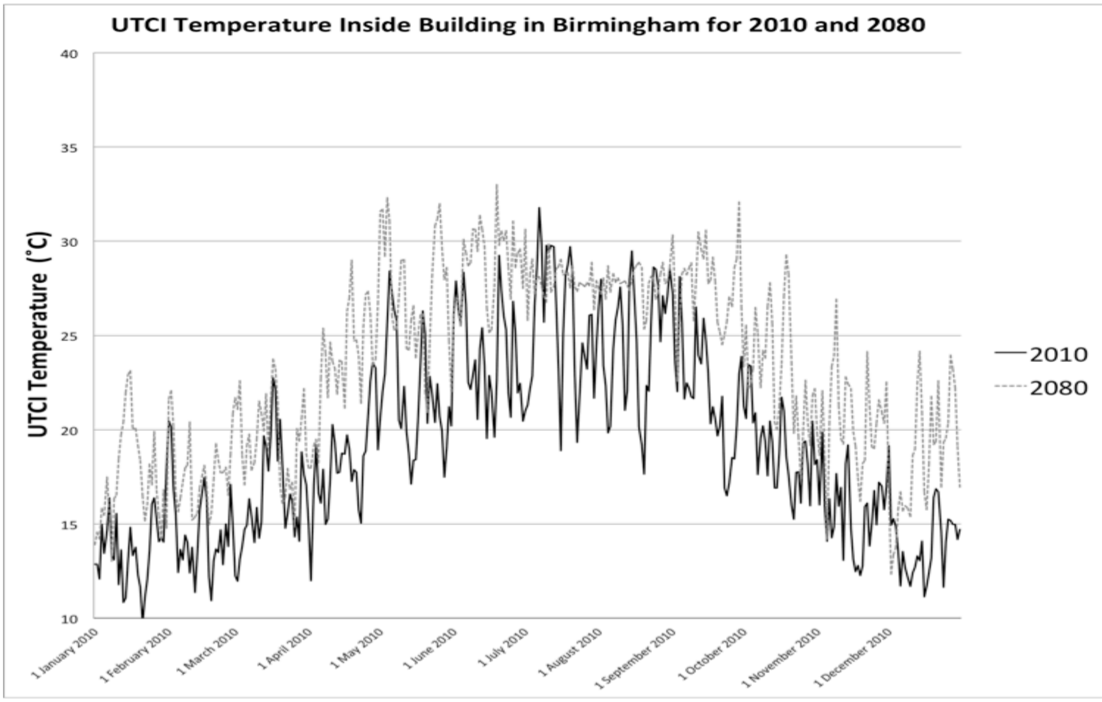

Figure 6-6: Daily UTCI temperatures within the building model for Birmingham in 2010 compared with UTCI temperatures generated using the surrogate model for 2080s using

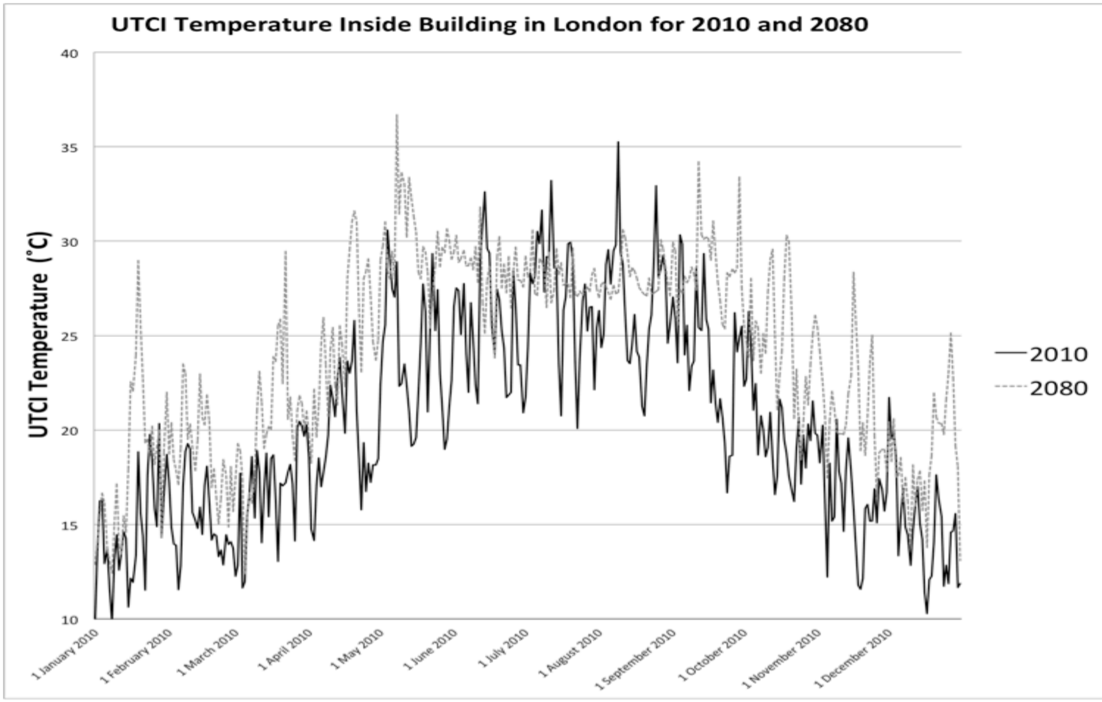

Figure 6-7: Daily UTCI temperatures within the building model for London in 2010 compared with UTCI temperatures generated using the surrogate model for 2080s

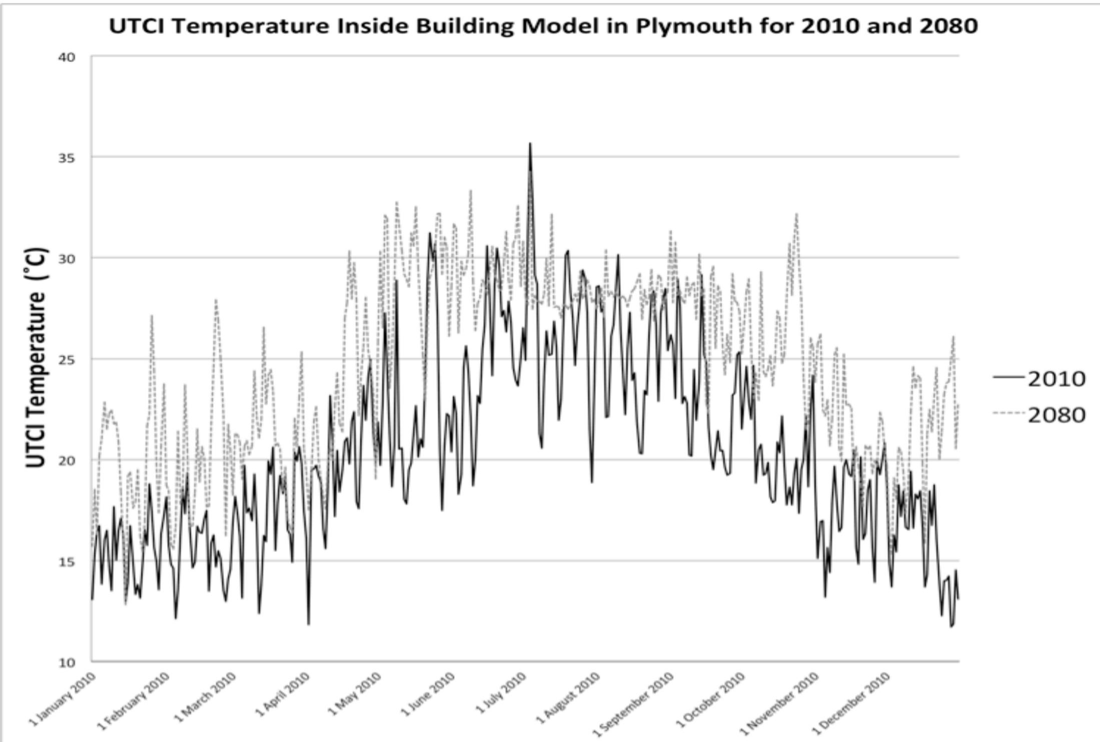

Figure 6-8: Daily UTCI temperatures within the building model for Plymouth in 2010 compared with UTCI temperatures generated using the surrogate model for 2080s

These plots reveal for the UTCI temperature of the internal environment of a building in probabilistic future weather based on climate change projections. The findings are significant, for they show a number of interesting features, which are broadly coherent across all locations. First that by 2080 it is possible that far more spikes in indoor UTCI temperatures will occur throughout the year than at present. Second that for several months in the summer, sustained high UTCI temperatures representing ‘strong or very strong heat stress’ (>26˚C) compared to today are possible. Third, that there is an underlying increase of mean UTCI temperatures of 4.2˚C in Birmingham, 3.8˚C in London and 4.4˚C in Plymouth.

The methods and results presented in this thesis show that it is possible to generate an accurate, working surrogate model to use in place of on-going CFD calculations performed to explore the outcomes of varying the input boundary conditions on a given geometry. Using the methodology outlined here it was possible to take outputs from CFD calculations on a building model and successfully produce a surrogate model, giving the ability to emulate heat stress results for analysing the effect of future weather on a habitable space. The emulator swiftly processed an entire calendar year’s worth of input parameters and analysis was conducted on the heat stress within the building.

6.3.8 Comparing the Emulator and *EnergyPlus*

One criticism of the above process is that it may be possible to simply estimate the UTCI temperature from *EnergyPlus.* This can be done by taking output values from an EnergyPlus simulation and an assumed low air speed (one can make the assumption that the air speed is a low constant in the room, set to 0.15ms^{-1}). If the values were only marginally different, then it may demonstrate that using the DSM could give similar results for less effort. However, comparing the EnergyPlus outputs to the CFD emulator outputs reveals a difference between the values, as shown in the three regional plots **Figure 6-9**, **Figure 6-10**, **Figure 6-11**. This indicates that it is indeed worth going through the CFD and emulator process.

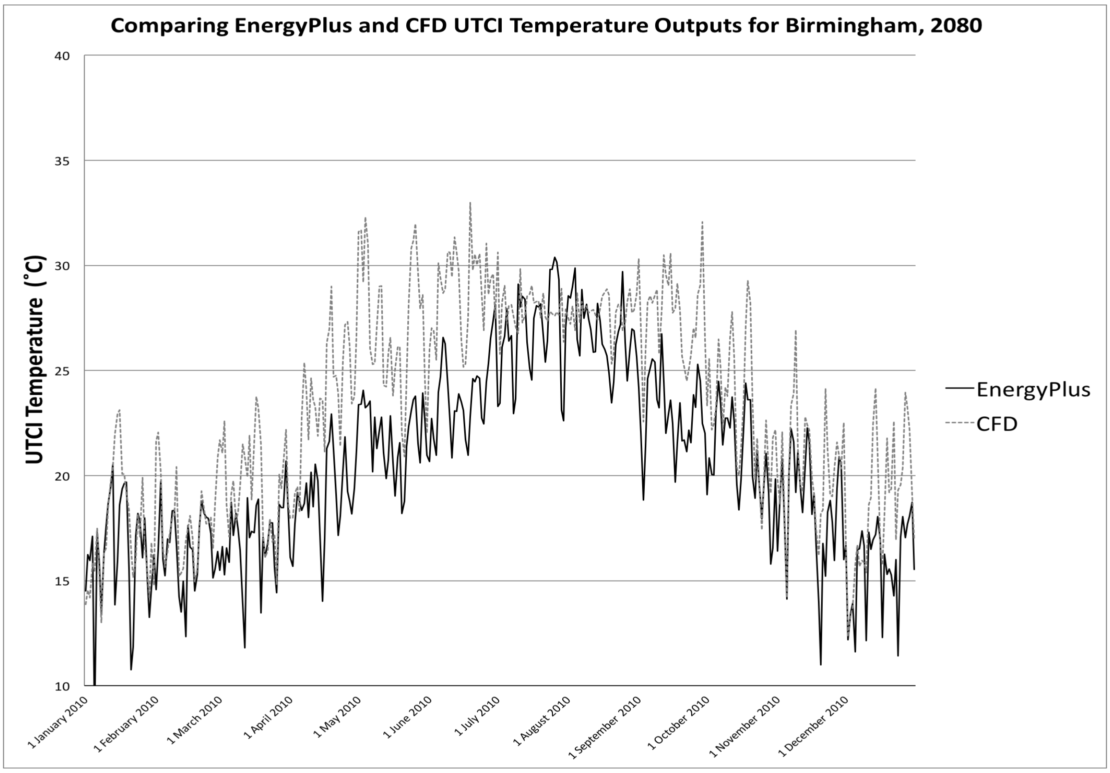

Figure 6-9: Daily UTCI temperatures generated by EnergyPlus are compared with UTCI temperatures generated using the surrogate model for Birmingham for 2080s

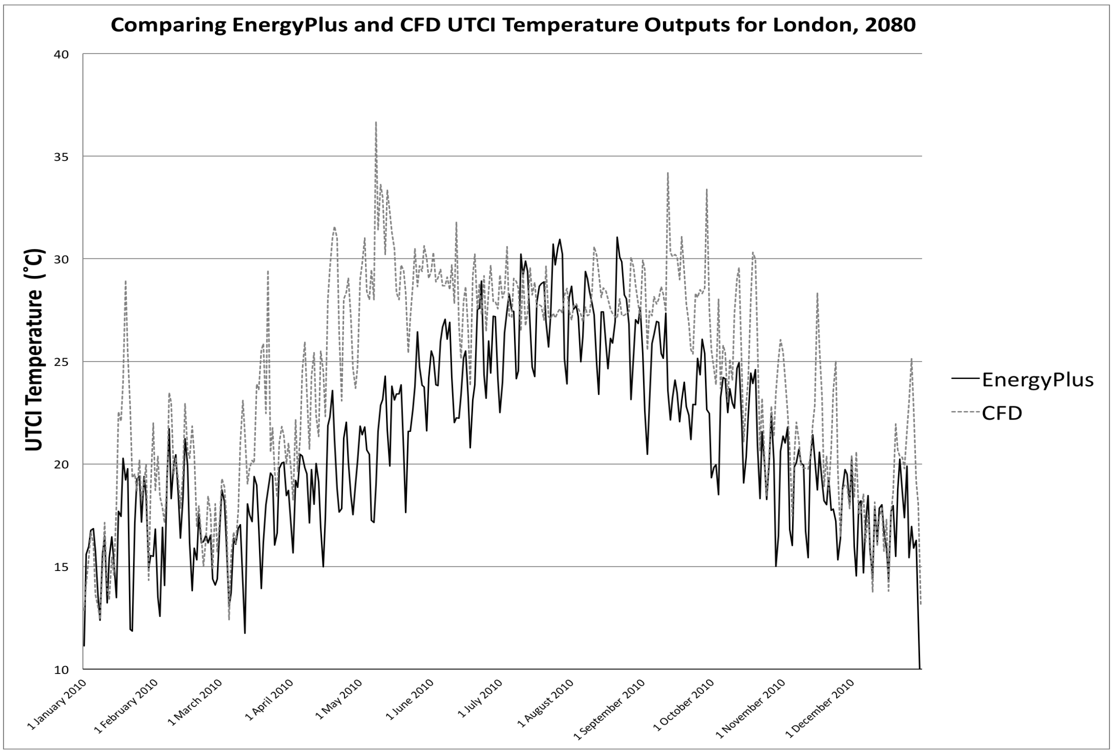

Figure 6-10: Daily UTCI temperatures generated by EnergyPlus are compared with UTCI temperatures generated using the surrogate model for London for 2080s

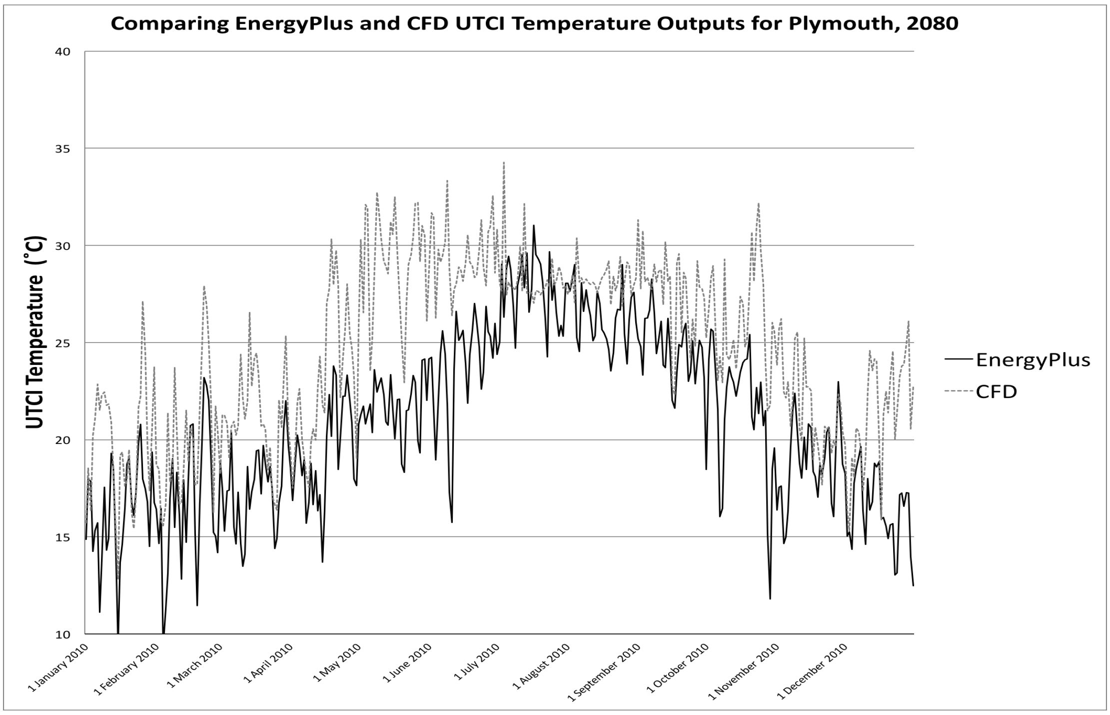

Figure 6-11: Daily UTCI temperatures generated by EnergyPlus are compared with UTCI temperatures generated using the surrogate model for Plymouth for 2080s

6.4 Surrogate model considerations

6.4.1 Further development of the surrogate model

At present the model is restricted to the specified geometry, and whilst setting up and running a spread of models with different boundary conditions is relatively straightforward (if time-consuming), introducing geometric design parameters into the mix would make the process significantly more complicated. The surrogate model creation process requires a significant number of CFD runs to be carried out in order to produce the output values to train the emulator. Once created, the model is independent of the mesh but valid for that geometry alone. Full CFD simulations could be undertaken for case specific parameters, and a surrogate model could be created to emulate CFD results, when it is desirable to have a model for a specific building which can be investigated for a range of climatic parameters. To take full advantage of surrogate modelling, the generation process could be automated or generalised to cover particular variations in the building. Once the emulation process is automated, then full outputs from the CFD simulations could be inputted into the emulator. By doing this, it could then be possible to extract spatial information from the CFD data. For instance, single cell-averaged UTCI values for multiple localised regions within the space could each be inputted and processed by separate emulators, resulting in a spread of UTCI values within the space. 5 points per room dimension would give 5x5x5 = 125 equally spaced temperature values per room, which would allow surface plotting and richer analysis of the temperature differences or 'hot spots'. This would certainly mark an advancement of the surrogate model process, and indeed give even more justification for utilising CFD in thermal building analysis.

6.4.2 Considerations for surrogate modelling in building design

Perhaps one of the most appropriate uses for surrogate modelling of internal heat stress is in the design of habitable spaces that have relatively fixed geometries. This would include specific structures such as offices, public spaces such as concert halls or shopping malls, where the initial setup could be justified. Other applications could include HVAC applications in the automotive and aerospace sectors. For instance the number of different aeroplane geometries is relatively low, and the internal cabin geometry of most vehicles does not vary greatly. If a surrogate model of internal heat stress could be produced for these cases, with perhaps the number of occupants being a given parameter, then this would serve a useful tool for internal thermal comfort. This thesis has shown that if a case warrants the time and resources spending on it, it is possible to explore a full range of climatic parameters and their effect on the internal environment at the design stage.

A surrogate model is not able to achieve full accuracy and the trade-off for expediency is adding another step to the modelling process and a degree of inaccuracy. CFD run times of thermal heat stress calculations in the building model took hundreds of hours to converge to a solution, whereas the surrogate model, once created, took just seconds. Whether the time-consuming surrogate creation set-up is worth it depends on how essential it is to explore the outcomes of the various input parameter combinations. For a high-cost habitable space it may be the case that engineers would want to check all potential overheating outcomes before embarking on construction of a potentially flawed design, and deem the surrogate generation expense worthwhile given the model's ability to explore the entire parameter space. Arguably the technique is worth the trade-off, especially since accuracy can be maintained at >90%.

6.5 Chapter summary

This concludes the chapter on localised internal heat stress. A method was developed using CFD to simulate heat transfer and fluid flow inside a building in a variety of weather conditions. A surrogate model was developed to emulate internal heat stress results from the CFD simulations, so that any combination of the environmental parameters could be rapidly assessed for thermal impact on the internal conditions. With a successfully created surrogate model, future weather conditions could be passed through a building model and thermal testing could be applied to analyse the predicted internal heat stress, based on climate projections.

7 Summary

All of physics is either impossible or trivial.

It is impossible until you understand it,

and then it becomes trivial.

Ernest Rutherford

7.1 Conclusions

Heat wave conditions in the UK are currently described as two days of maximum daily air temperatures exceeding 30-32˚C, with a minimum intervening night-time temperature. If these hot weather conditions are met, then public health warnings are issued. I have found a more accurate metric to predict health risks in hot weather is the Universal Thermal Climate Index (UTCI>97.5th percentile) (see **Figure 4-10**). If the maximum UTCI temperature exceeds the 97.5th percentile on a given hot day, there is a strong correlation with significant excess deaths on the following day. This one-day time lag between high temperatures and high mortality rates was also found in **Figure 4-5**, **Figure 4-6** and **Figure 4-7**, backed up by other studies, suggesting a need to reconsider how heat waves are defined, and whether individual hot days suffice for triggering health risk warnings.

The move away from air temperature toward UTCI temperature would be significant, but makes sense. In hot weather conditions, with low airflow, strong solar radiative temperature and a humidity component, the equivalent temperature the human body feels is approximately 2˚C warmer than the air temperature. The fact that we feel warmer in such conditions than the temperature on a dry bulb thermometer may explain why results indicate significant excess deaths are occurring at 2˚C below the Met Office heat wave thresholds. The greatest risk of using UTCI to issue public health warnings is that the additional weather parameters, such as air speed and solar radiative temperature, would need to be closely aligned to the forecast location. At present this is not possible, due to the lack of sites where these parameters are measured. However, it may be possible in the future to deduce values for some of these parameters using satellite data. For instance, technical researchers at the Met Office, with whom I have met, have verbally confirmed that they are attempting to gain solar radiative data this way, for the purpose of improving the current heat wave warning process.

It has also become evident in this thesis that since people spend the majority of time indoors, the quality of the indoor environment is fundamental to human health. The internal environment is directly linked to the outdoor weather conditions, and the UTCI metric can be used reliably for setting peak threshold limits indoors, since it better represents the equivalent temperature that the human body feels given environmental weather parameters. The reference building used in the process is designed to be a room measuring 5x5m with a single, slightly ajar window. This is similar in many respects to a main room in a city apartment, and this is the type of building that many people who became heat stress victims in the European 2003 heat wave inhabited. UTCI temperatures could potentially be higher in a real building scenario, and so the reference building, which provides a proof of concept for this UTCI peak threshold work, certainly needs adapting for application in actual building scenarios. For instance, ventilation modelling would need to be included, since if the ventilation rates are lower, for instance in an apartment where windows cannot be opened, UTCI temperatures would probably be higher. New peak temperature thresholds have been established for the built environment, but this thesis suggests that if air temperature is retained as the main building overheating metric in criterion 3 of CIBSE TM52 ΔT should be no greater than 3˚C. This means that the temperature difference between the indoor operative temperature and the maximum temperature threshold for thermal comfort should be revised down. This is not altogether surprising; given that we have seen throughout the findings in this thesis that threshold temperatures for health are consistently higher than they ought to be. Consequently, this finding adds weight to the argument for using the UTCI metric to test for overheating in buildings.

The current method of modelling thermal performance in the building design industry, using software packages such as *IES* and *EnergyPlus*, with current DSY reference weather data and treating indoor conditions with bulk parameters is inaccurate. To address these issues, first; new DSY reference weather data has been developed using the probabilistic return period methodology, and now includes a suite of reference weather data that can be used to test for heat stress using new UTCI-DSYs in near extreme and extreme weather conditions and in future climates. Second; CFD simulations of indoor heat stress have been calculated for a simple building model, and a surrogate model has been created to rapidly test for indoor heat stress in any weather conditions, current and future. The findings in this thesis show that in the future we could possibly expect more spikes in indoor UTCI temperatures throughout the year than we do at present, and that we could see several months of sustained high UTCI temperatures representing 'strong or very strong heat stress' (>26˚C) compared to today. The challenge for the building industry is whether engineers can adapt designs for new buildings with these possible future internal conditions in mind.

There is still clearly a great deal of research to do in the field of thermal comfort and heat stress, to aid the development of building design. Buildings can last for centuries, and designing them to keep us healthy and comfortable for future climates, together with a common will to neutralise carbon emissions, must surely be one of the most fundamental challenges facing the building profession. As scientists, our role is to give building professionals the data, standards and tools to aid them in this task.

7.2 Further work

7.2.1 Distinctions between thermal comfort and heat stress

There is a grey area between thermal comfort and heat stress that needs investigating to help define the health risks for the future, and a study should look at the differences in health effects between simulations using an adaptive heat balance equation, and heat stress models. The focus of this thesis was researching the threat to human health inside buildings in hot weather, and to investigate the health effects in a changing climate. As a result, research was concentrated on heat stress and establishing peak temperature thresholds for buildings; however an area that would benefit from more extensive investigation is thermal comfort. Thermal comfort has partly been addressed in this thesis, namely in the background research and in the reformulated near-extreme DSYs in chapter 5, though it is evident that the building industry could incorporate adaptive thermal comfort models and allow user-controllable boundary conditions, rather than using default input parameters in building modelling software. Further work might identify that overheating criteria may require greater emphasis on people’s adaptability to control their own thermal comfort.

7.2.2 Health metric considerations for extreme weather

In this thesis research has focussed on mortality as the primary health impact metric. Further work should also consider other health metrics such as heat related diseases to develop peak threshold temperatures. Another potentially useful metric would be a productivity-based measure. Productivity is already an important measure in the building industry, because the clients funding commercial constructions are property developers and employers will demand comfortable conditions for their staff and customers, so that productivity is not compromised. A recent study for instance indicated that productivity can fall by 3.6% for every 1˚C over 22˚C [164]. Further work could also be carried out on the effects of night-time temperatures on health, for these were not analysed in this thesis. The physiological effects of high temperatures on the human body at night are accentuated by a person's inability to actively adapt whilst sleeping, and this should be investigated in particular. The other consideration especially relevant to night-time temperature is the 'Urban Heat Island' (UHI) effect, where energy stored in the thermal mass of concrete and building material during the day in a city centre is released overnight when there is a greater environmental temperature gradient, resulting in increased night time air temperatures. This effect may however not be an issue in this thesis, where the heat stress effects of single day extremes have been established and two-day events were not the focus.

Another area that could be further investigated is the development of threshold metrics for other types of extreme events. In this thesis the research focus was directed toward extreme hot events, as the health impacts from hot weather were found to be the most severe in chapter 3. However, there is no reason why the method developed to analyse hot weather in chapter 5 could not be employed to create annual frequency forecasts of other weather events, such as floods, storms and cold events, and a suite of extreme weather definitions could be developed with corresponding peak threshold metrics, be they health-related or otherwise, to cover all risks.

7.2.3 Developing the CFD and surrogate models

The building model described in chapter 6 of this thesis is a simple one-room construction, with a single window and a small inlet and outlet for ventilation. This geometry was chosen for its simplicity, since its purpose was a proof of concept. For CFD modelling it is possible to create any required geometry, to add objects to the space and include dynamically coupled elements such as human bodies with interactive thermo-regulatory properties; although due consideration must be paid to keeping the number of parameter variables to a manageable number for the surrogate model construction.

In essence the method outlined in this thesis has a number of applications and further research could be undertaken to benefit from these techniques. Future development of this work could include creating surrogate models that emulate CFD simulations of thermal comfort in different building geometry types. It could also include applying the technique to thermal comfort analysis in the automotive and aviation industries. In vehicles and aircraft, geometric developments to the designs are fairly minimal and incremental, so CFD calculations could be focussed on performance parameters of a given mesh under external environmental conditions. Outputs from CFD models could then be passed through a surrogate modelling process and performance of the mesh could be rapidly tested against any number of environmental permutations. If this were achieved then simple software applications could be developed for design engineers in many industries to perform in-depth analysis on chosen parameter performance. Users could select a geometry from an application menu, along with the parameters they wish to test, as well as the desired output, such as heat stress as used in this thesis, air flow or particulate dispersion for example.

7.2.4 Coupling human body models with indoor environments

Further research could also extend the CFD and surrogate modelling methods to coupled models between human bodies and indoor environments. For human health indoors it may be helpful to ascertain the heat distribution around a human being in a hot indoor environment, thereby simulating the heat stresses that a person could be exposed to. CFD can be employed to map out the thermal distribution in an indoor space and examine the localised physiological conditions that prompt peoples' perceptions of discomfort, by looking at indoor conditions that limit the thermal impact on particular parts of the body. Results could then be simulated based on adaptive thermal comfort principles in naturally ventilated buildings, such as opening windows and removing layers of clothing, to show if it is possible for a person to adapt to internal conditions and remain thermally comfortable. The multi-node Fiala-human model has already been coupled to an indoor space for CFD analysis [40], and the *FORTRAN* code and the CFD work performed using *ANSYS Fluent* could be translated for use in *OpenFOAM* and subsequent surrogate modelling. Such work could look at localised UTCI temperatures around the human body in particular, allowing the effects of heat stress around the body to be simulated in hot weather conditions, such as those considered in this thesis. This would also allow further analysis of localized discomfort. For instance, the UTCI value used as the primary metric in this thesis gives the heat stress equivalent for the cell-averaged internal environment, yet the output could be adapted from the CFD simulation results to focus on hot spots or temperature gradients, or if there are areas in the building where a person would be exposed to large differences in heat stress, which could lead to localized thermal discomfort. This research could be valuable in attaining a complete view of how overheating affects people's health, since the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) not only emphasises the need for general macro comfort conditions, but also that people should feel ‘no local discomfort at any part of the human body due to, for example, asymmetric thermal radiation, draughts, warm or cold floors, or vertical air temperature differences’ [21]. CFD would facilitate a detailed look at localised heat effects, needed to qualify ASHRAE’s local comfort criteria above, and to dynamically model heat stress parameters; something not currently possible in standard building software packages such as *IES* and *EnergyPlus*.

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