Predicting temperatures within buildings and the heat stress on occupants under substantial climate change

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Introduction

The level of future climate change is uncertain and depends on many physical, social and political factors. estimates of change for the UK can be obtained from the Climate Impacts Program projections (UKCP09)[1]. These estimates include probabilistic projections for a range of climate variables and emissions scenarios allowing an evaluation of risk. However, the observed time-series of recent carbon emissions indicate that the climate change could be greater than the IPCC A1FI emissions scenario[2], hence the use of upper percentiles of the CDF probabilities included in the UKCP09 projections in this work as well as medium estimates. Although this implies that global mean temperatures are set to increase alarmingly the public are unlikely to respond as they are more cognisant of weather than climate. In this work we show that possible future weather under extreme climate change has serious implications for the built environment. Using a thermal model of an elderly rest home we investigate the effect on the internal environment and the consequences on the thermal comfort of its occupants.

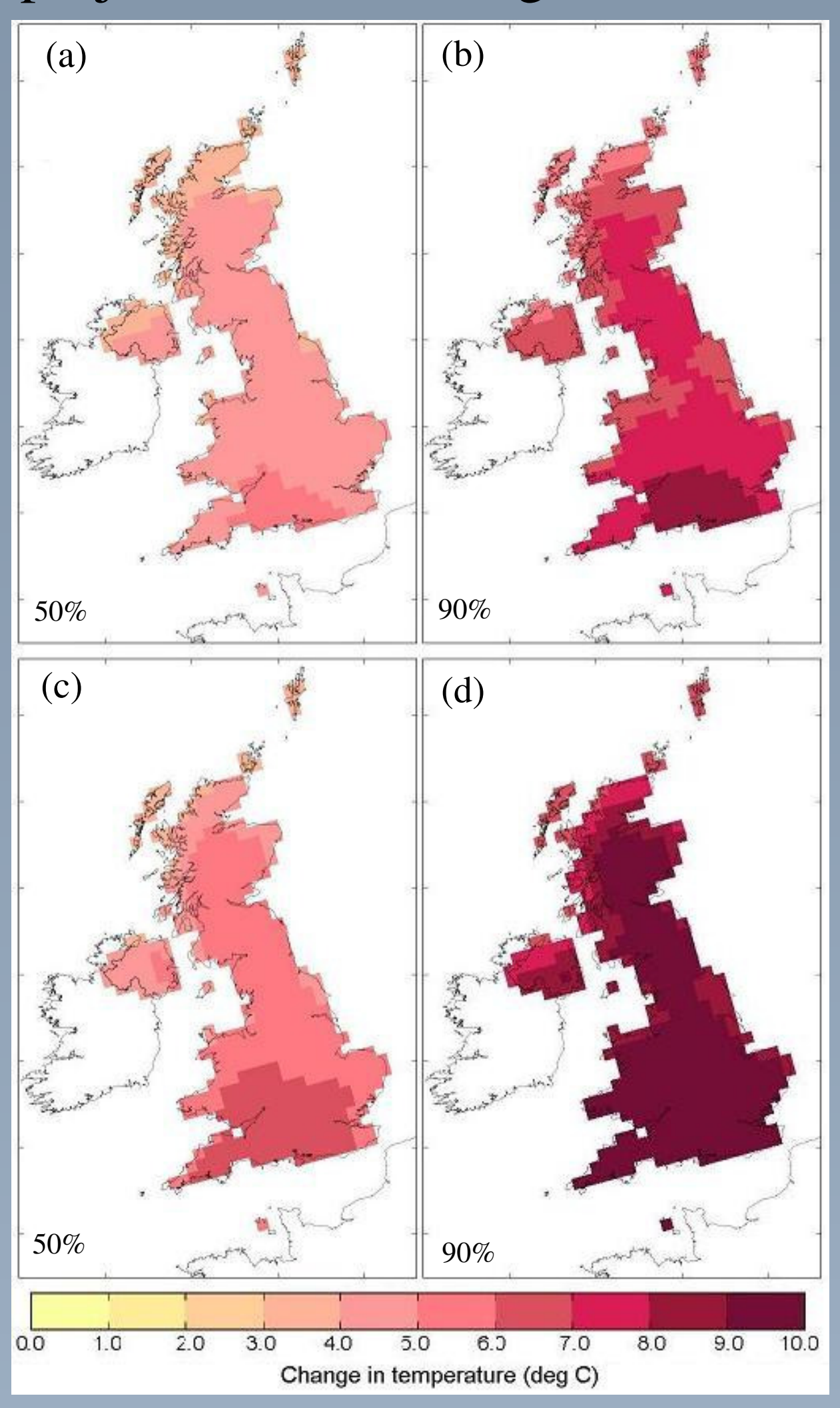

Figure 1. Projected changes of summer average daily mean (a and b) and mean daily maximum (c and d) air temperature in the 2080's for the 50 and 90% percentile levels and the A1F1 emissions scenario.

The heat wave of 2003 demonstrated that the overheating of buildings can have severe consequences for human health, productivity and performance. In Europe approximately 35,000 excess deaths – mostly among the elderly – were attributed to heat stress[3]. Projected changes for the summer mean daily temperature and mean daily maximum temperature are shown in figure 1 for the A1FI emissions scenario in the 2080s[1]. The central estimate predicts summer mean UK temperatures up to 5.3°C warmer (~2°C greater than 2003 mean summer temperature) and the mean summer daily maximum temperature to be up to 6.8°C warmer. Using the 90th percentile these values increase to 8.4°C and 11.7°C respectively. Although the high summertime temperatures in 2003 were estimated to be a 1-in-1,000 year event, by the 2040s such a summer is expected to be about average, while in 2080 it could be anomalously cold[4].

Future Weather

Simple mathematical transformations, commonly known as morphing[5], can be used with the UKCP09 climate anomalies to generate future weather. Hourly weather data for the current climate is adjusted using the predicted monthly-mean climate change values (output from UKCP09) to generate a future hourly time series[5]. The morphed time series has the benefit of starting from observations of the required location and the variables are self consistent. However, it doesn't allow for fundamental change in the weather patterns.

The morphing procedure uses three operations:

1. A shift of the base climate by the addition of a mean value when the climate change scenario lists an absolute change
2. A stretch of the climate variable when the change is defined as a percentage
3. A combination of both a shift and a stretch when the mean and variance changes.

Figure 2 shows the dry bulb temperature for Heathrow in 1989 (the Design Summer Year[6]) and morphed weather for 2080 (90th percentile, high emissions scenario). Peak daytime temperatures are seen to be considerably higher.

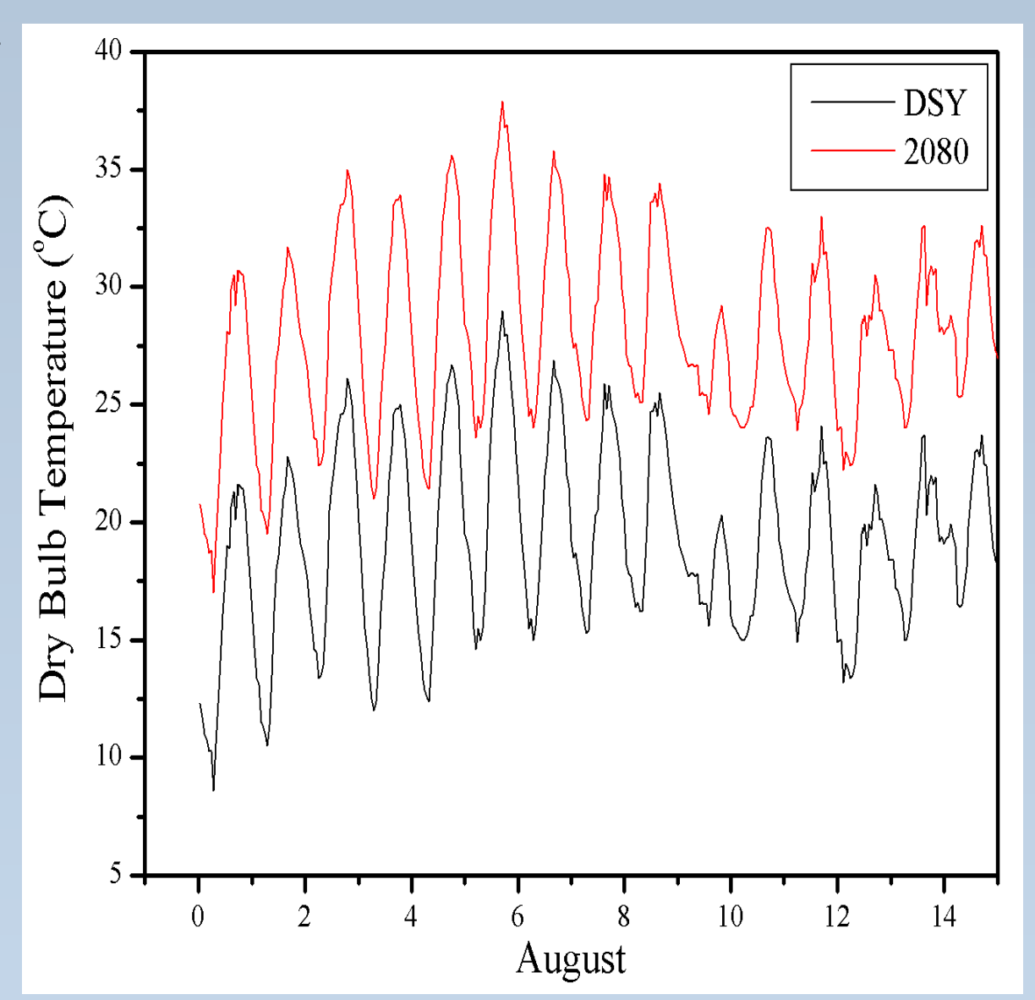

Figure 2. August Dry Bulb Temperature for the Heathrow DSY and Morphed DSY using UKCP09 2080 90th percentile change factors.

Heat Strain

Heat strain is dependent on air temperature, radiant temperature, humidity and air speed as well as non-climatic variables such as clothing insulation levels, acclimatisation, fluids intake and metabolic rate. Under heat stress the body temperature may rise leading to increased blood flow within the skin and sweating if necessary to provide a mechanism for heat loss. If this mechanism is not sufficient heat storage can occur. If the core temperature increases to beyond 38°C collapse may occur and beyond 40°C heat stroke is likely.

The heat strain can be calculated by balancing the flow of heat to and from the body[7]. The evaporative heat flow required (E_{req}) for the maintenance of thermal equilibrium of the body is given by,

$$E_{req} = M - W - C_{res} - E_{res} - C - R - \partial S_{eq} \, , \qquad (1)$$

where M is the metabolic rate, W is the mechanical power, C_{res} and E_{res} are the heat exchange due to respiratory convection and evaporation respectively, C and R are the heat flow by convection and radiation at the skin surface and δS_{eq} is the heat stored due to the metabolic rate.

The maximum possible evaporative heat flow is given by the balance of the saturation vapour pressure at the skin temperature ($p_{sk,s}$) and the water vapour partial pressure (p_a) given by,

$$E_{max} = \frac{p_{sk,s} - p_a}{R} \, , \qquad (2)$$

where R describes the evaporative resistance of the immediate surroundings e.g. clothing, movements of subjects and air movement. If the amount of evaporation required is greater than the maximum possible evaporation, heat is stored in the subject.

Climate Change Amplification Coefficient

Many existing buildings exhibit levels of overheating close to the maximum allowed by the building regulations of the country in which they are located. It is highly likely that such designs will breach the regulations under even modest amounts of climate change. It has been shown that a simple metric the 'climate change amplification coefficient' C_T can be used to estimate the change in internal conditions within a building for any realistic amount of climate change irrespective of temporal range, emissions scenario or probability level[8]. This allows a rapid estimation of the internal environment and its impacts on human health as well as a rational comparison between different design and construction choices.

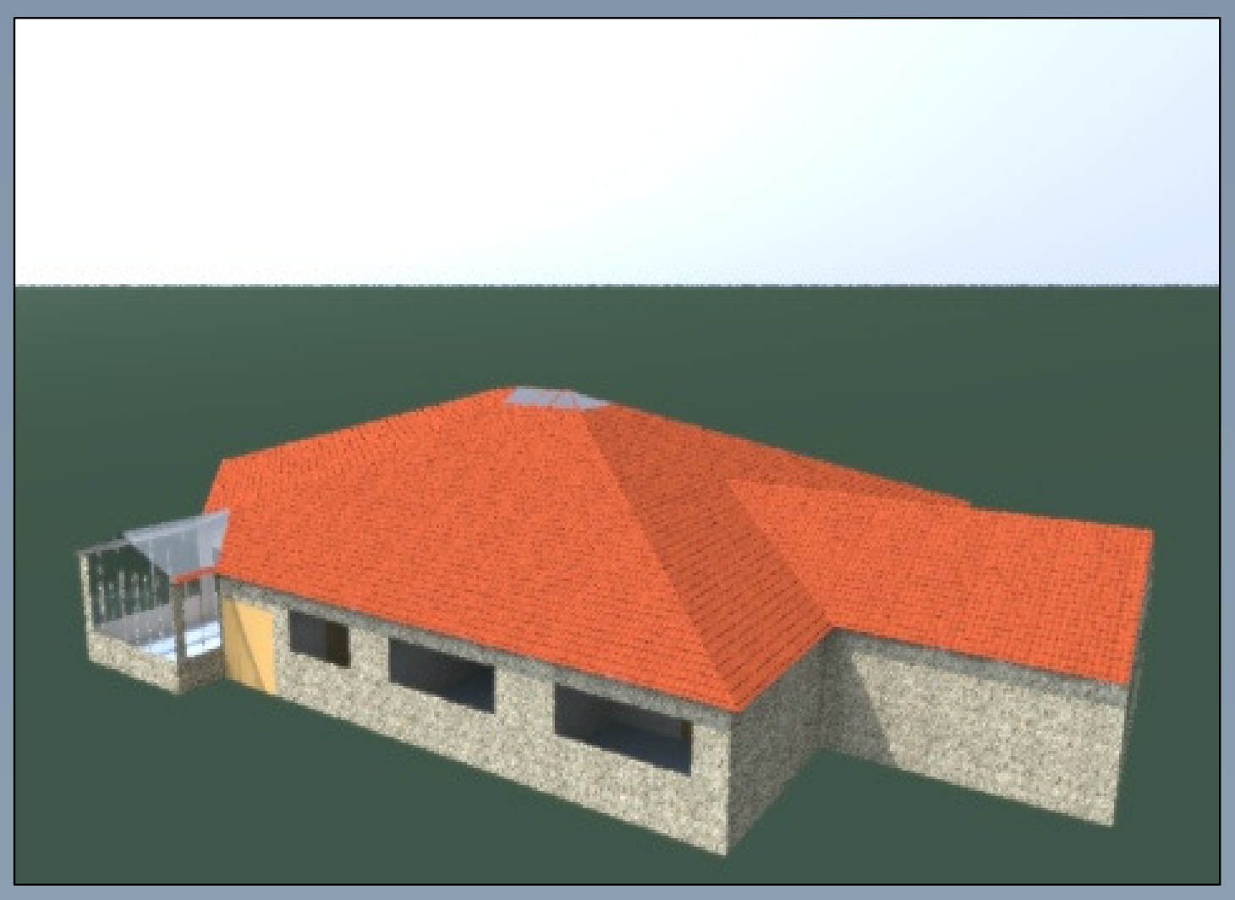

Figure 3. Rendering of the thermal model used in this study.

Two dynamic thermal models of a small rest home were created. All constructions within the model conform to 2002 UK building regulations. A rendering of the model is shown in figure 3; it is a single storey building with the entrance and a conservatory facing south. The first model consists of a brick construction with a cavity wall and plasterboard on the inside. The second model is a heavier weight construction with brick and block cavity walls and block internal walls. figure 4 shows the results of different climate projections on the buildings.

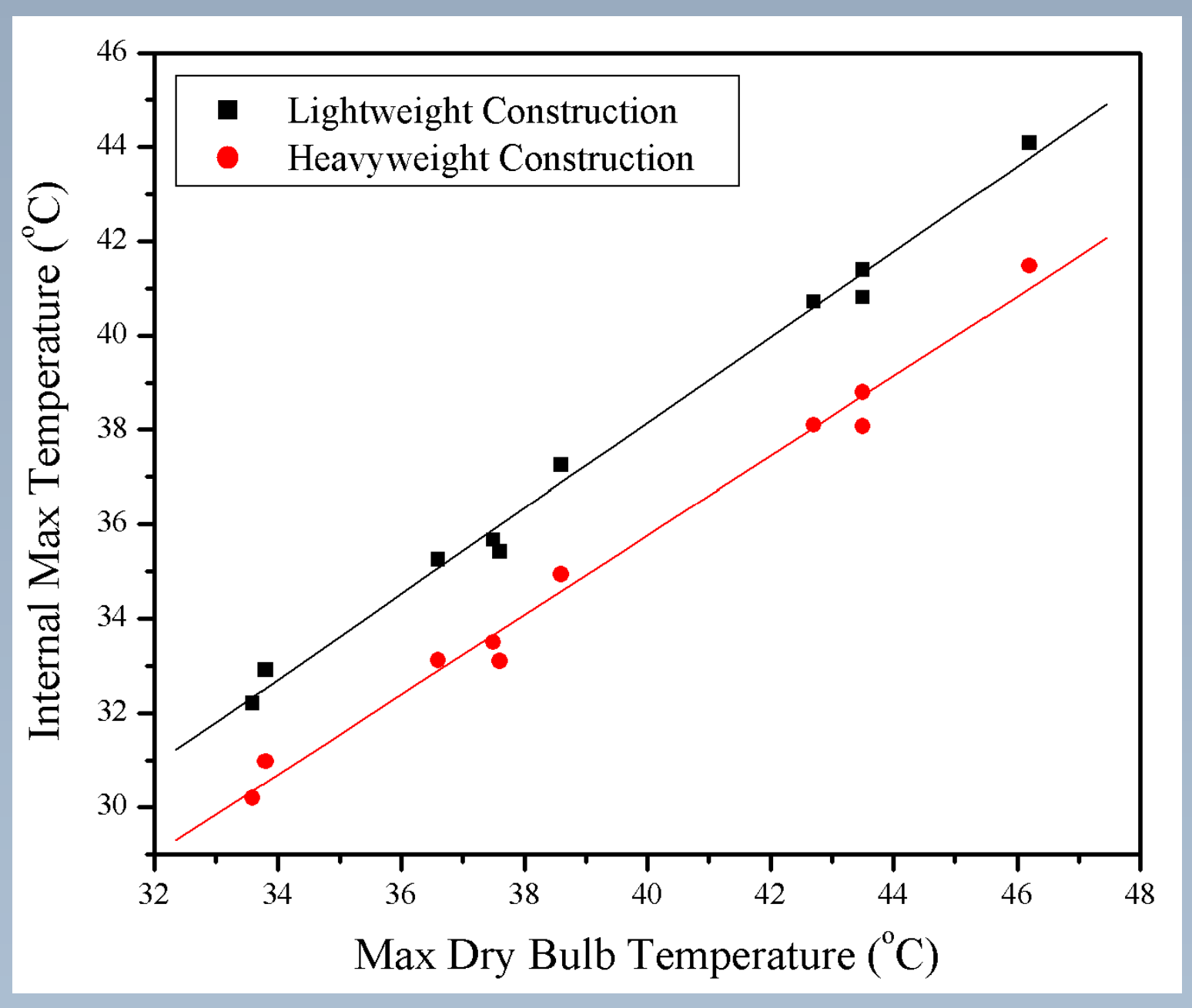

Figure 4. Plot of resultant internal maximum temperatures versus maximum external Dry Bulb Temperature using a range of morphed scenarios using UKCP09 change factors. The normal construction has a gradient of 0.91 while the alternate construction has a gradient of 0.84.

A linear response is found between internal air temperature and external maximum dry bulb temperature. The heavier weight construction has a lower gradient corresponding to a lower C_T value of 0.84 compared to 0.91 for the lower weight construction. In both cases the correlation coefficients are very high ($R^2 > 0.99$).

In practise this means that the heavyweight construction could suppress the effects of possible climate change in comparison to the lightweight construction. That is in this case, for each degree of warming in the external maximum temperature, the internal maximum temperature of the lightweight construction increases by 0.91 degrees. In comparison, the internal maximum temperature of the heavyweight construction increases by only 0.84 degrees.

Final Results

The dynamic thermal models of the building were used together with the morphed time series of weather shown in figure 2 (2080, high emissions scenario, 90th percentile) to predict the air temperature, humidity etc within the building. This was then used with the heat strain model[7] to assess the impact on the occupants.

The internal air temperature is shown in figure 5. It is shown that the heavyweight construction is able to maintain a lower internal temperature than the lightweight construction for most of the time period with peak temperatures up to 4.5°C cooler. However, once the thermal mass has been sufficiently warmed the effect is suppressed.

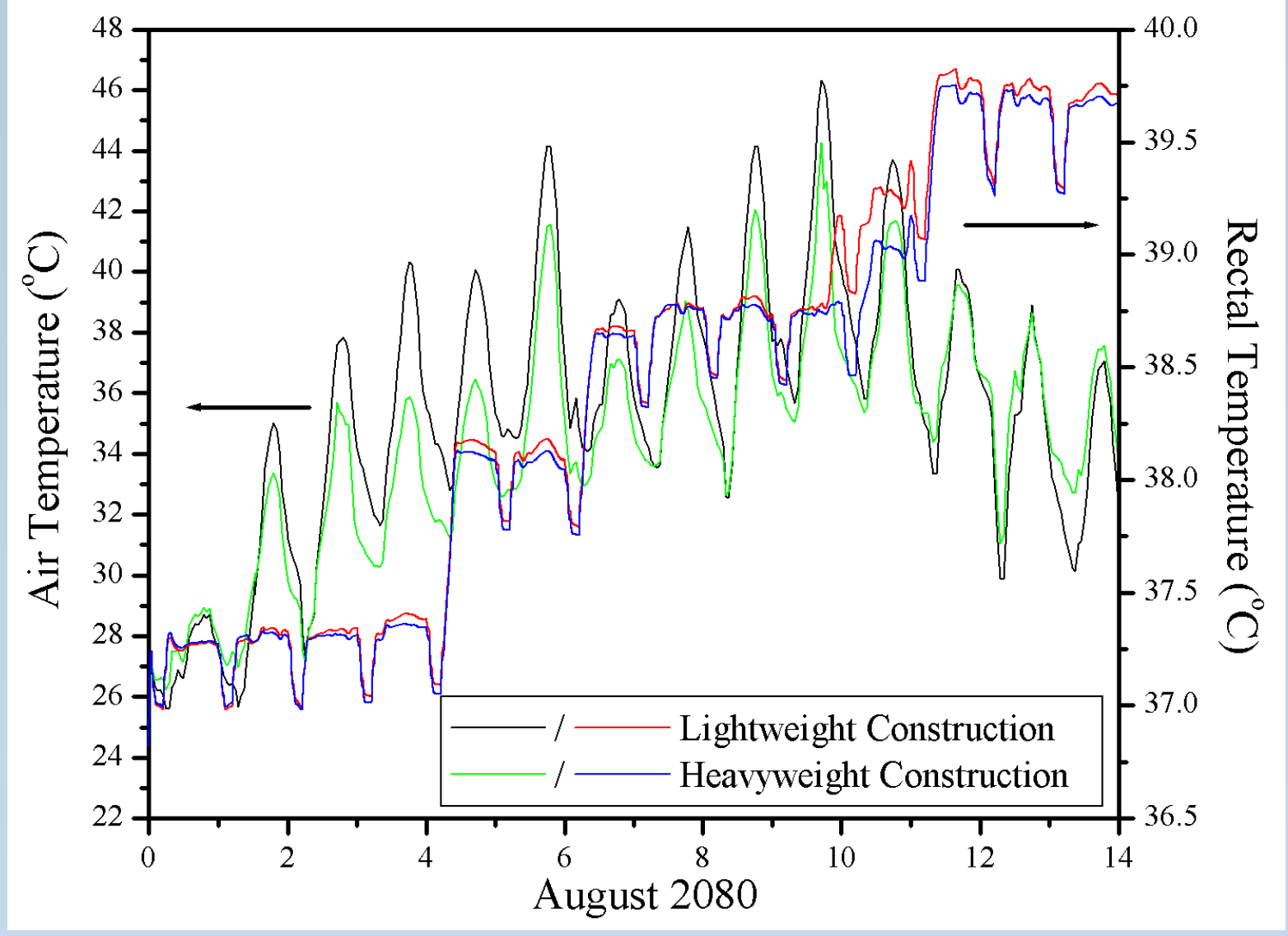

Figure 5. Plot of rectal temperature and internal temperature for the first 2 weeks of August 2080. Data is morphed from Heathrow 2003 observations using the UKCP09 90th percentile of the high emissions scenario. Both heavyweight and lightweight building constructions are considered.

The effect of the internal environment on the occupants is shown in figure 5 as the rectal temperature. The calculation used clothing insulation and activity levels (metabolic rate) typical of elderly rest home occupants. The subjects were assumed to be un-acclimatised but able to drink freely (in this case we are ignoring the effect of hydration). The rectal temperatures are above the 38 °C limit imposed by the WHO for prolonged daily exposure for both constructions. Although the heavyweight construction gives rectal temperatures lower than the lightweight construction the difference is negligible. In each case the rectal temperature increases to above 39.5 °C after August 11th despite a decrease in air temperature over the same period, indicating that the human body is at an increased risk of heat stroke. Note that despite the metabolic rate and activity levels adjusted to represent elderly rest home occupants there is no inclusion in the model of age or infirmity (it has been shown that the elderly have a reduced ability to respond to heat strain[10]), hence, the results shown in figure 5 should be treated as a lower bound.

Conclusion

Using careful construction processes it is possible to design buildings which can suppress the effects of climate change and maintain lower internal temperatures. A simple metric (the climate change amplification coefficient) can be used to compare similar constructions and make rational decisions with regard to the ability of a particular building's ability to cope with a changing climate. However, we find that thermal mass alone may not be enough to protect the occupants from potential heat strain.

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