CHARACTERISING THE RESPONSE OF BUILDINGS TO CLIMATE CHANGE: THE ISSUE OF OVERHEATING

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Summary: Many buildings currently demonstrate levels of overheating close to the maximum allowed by the building regulations of the countries in which they are located. Therefore there is the potential that such buildings will clearly breach the regulations under the climatic conditions predicted as a result of climate change. To examine the problem, weather files indicative of possible future climate were created and applied to a variety of buildings. We have found that the projected levels of climate change engender a linear response in the internal temperature of the buildings. We have termed the constant of proportionality that this implies the 'climate change amplification coefficient'. We suggest that optimisation of the climate change amplification coefficient during the design process of a new building will promote the adaptation of architectural design to the effects of climate change and thereby improve resilience.

Key Words: Climate change, overheating, resilience, adaptation, building, internal environment, climate change amplification coefficient.

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I. INTRODUCTION

There is now an overwhelming body of scientific evidence suggesting that climate change is an urgent and serious issue. Predictions of the world' climate point to an increasingly warmer world, with greater warming across land and away from the equator (IPCC, 2007). Predictions contained within the IPCC's fourth assessment report (AR4) indicate mid-latitude mean temperature rises over land of ~4°C (under the A1FI scenario) (IPCC, 2007). However, recent research (Anderson, 2008) shows that current emission trends imply that the actual temperature increase could be far higher than predicted by the A1FI scenario. This implies that several highly populated regions not used to high temperatures will be exposed to a very different summer time experience. In the absence of any human modification of climate, temperatures such as those seen in Europe in 2003 have been estimated to be 1-in-1,000 year events. However modeling by the Hadley Centre shows that, by the 2040s, a 2003-type summer is predicted to be about average (Stott, 2004) and this will clearly have a great impact on the energy consumption of air condition spaces and the thermal comfort within non-conditioned ones. In order to assess the scale of the problem there is the need to understand the sensitivity of the internal environment of buildings to changes to climate, and the sensitivity of the occupant, particularly of vulnerable groups. Here, we deal with the former, and attempt to quantify the response of all naturally and mechanically ventilated, non air-conditioned, buildings to changes to summertime temperatures. A reliance on air-conditioning, rather than careful architectural design will exacerbate the problem of climate change, due to the implied increase in carbon emissions. Given a quantitative scale of response, it should be possible to assemble risk registers of buildings and occupants, to improve the design of new buildings, and initiate the refurbishment of existing ones such that they are more resilient to a changing climate.

It seems natural to expect the response of a building to a perturbation in climate to be complex, with the functional form of the response depending on the degree of climate change and whether this is mainly a result of changes in, for example, wind rather than sunlight or air temperature rather than humidity, and on the architecture, construction materials, ventilation strategy and controls present. The existence of such a complex response function would make it difficult to discuss in any simple way the relative benefits of one design over another, or even characterise the response of a building with a single measurable statistic. For example, it might be possible that one design demonstrates little change in internal temperature for small perturbations to the external climate, but then a large and rapid response for greater perturbations, and that another design might show the opposite response. In such a situation it would be very difficult to draw any simple conclusions as to which design is likely to perform better under any particular climate scenario. Instead, we would need to complete a substantial amount of costly computer modelling to report a time series of changes given a time series of exact predictions of climate change within the urban environment. Climate science has yet to be able to give such predictions with the required accuracy, and even if it could we might be in the situation where, for example, one building design outperforms another until 2040 and then under performs the alternative design. Again, we are trapped by the potential complexity of the relationship between the building and its driving forces, making it very difficult to draw general conclusions and drive the adaptation agenda forward.

In this paper we investigate the form of the response function of a large number of buildings given a range of predictions of future climate. From this work we conclude it is possible to derive a single set of coefficients that fully describe the expected response of any design to any reasonable amount of climate change. We further suggest that these coefficients can be used to establish a definition of climate change resilience within architectural dialogues and set minimum performance standards within building regulations and codes, with the aim of promoting adaptation to a changing climate.

1. Prediction of Future Weather

Given statements of future climate by the IPCC and others (Murphy, 2000) a time series of typical future weather can be assembled in one of several ways, for instance by using recorded historical data for locations whose current climate matches that predicted for the location in question. This has the downside that certain weather variables such as hours of daylight, will be incorrect. Other methods include interpolating (in space and time) the time series produced by a global circulation model, or to run a fine (in space and time) regional climate model connected to a global circulation model. All these methods have advantages and disadvantages, which are discussed in more detail in Belcher (2005)

Belcher (2005) have developed a methodology for transforming historic weather files into future weather years representative of different climate change scenarios by the use of a set of simple mathematical transformations. The simplicity of this method has made it attractive to building scientists. In this method hourly weather data for the current climate is adjusted with the monthly climate change prediction values of a regional climate model (in the case of the UK, the output from UKCIP02 (UKCIP, 2002)). This methodology is termed ‘morphing’.

The morphing process has the advantage that it starts from observed weather from the location in question, the variables output are likely to therefore be self-consistent and it is simple to achieve given the resources available to building scientists. However, it doesn’t allow for fundamental changes in the weather, with for example, weather systems following identical trajectories across the landscape. Table 1 shows summary statistics for some of the future weather times series created using morphing and used in this work. The IPCC AR4 (2007) shows the upper boundary of the A1F1 scenario to be 6.4°C however there is evidence that current emissions exceed even the A1F1 scenario (Anderson, 2008), as such it is prudent to include more extreme climate change. While the extreme scenarios may seem unrealistic with the Hi++ scenario representing almost a 10°C increase in mean temperature, in the absence of the more up to date probabilistic scenarios of UKCP09 (UKCIP) this represents an upper bound. This scenario is designed to lie in the tail of the UKCP09 distributions and account for missing climate feedbacks in IPCC AR4.

Table 1: Example Statistics for Historic and Future Weather for London.

Scenario	*Min Dry T(℃)*	*Max Dry T (℃)*	*Mean Dry T (℃)*	*δ Mean T (℃)*
Historic TRY	*1.10*	*30.10*	*14.71*	*-1.14*
Historic DSY	*0.00*	*33.60*	*15.85*	*0*
Low	*1.50*	*37.70*	*18.42*	*2.57*
Medium-low	*1.80*	*38.40*	*18.85*	*3.00*
Medium-high	*2.50*	*40.30*	*20.07*	*4.22*
High	*3.00*	*41.50*	*20.83*	*4.98*
Hi+L	*4.60*	*45.60*	*23.40*	*7.55*
Hi+m1	*4.80*	*46.30*	*23.83*	*7.98*
Hi+m2	*5.60*	*48.30*	*25.05*	*9.20*
Hi++	*6.00*	*49.50*	*25.81*	*9.96*

Table 1 shows example statistics for summertime dry bulb temperature (Dry T) for the test reference year (TRY) and the design summer year (DSY) (Levermore, 2006) for London. These files are currently used for energy and overheating analysis respectivly for buildings in the UK, and characterise a typical year (the TRY) and a hot but non-extreme summer (the DSY) chosen from a 23 year cycle. Also shown are statistics for future weather years indicative of the 2080's based upon the emissions scenarios of the IPCC (2007) and UKCIP (2002) created using the morphing process. The four extreme sceanrios Hi+L, Hi+m1, Hi+m2 and Hi++ were created by performing the morphing proceedure twice. Figure 1 shows traces of external air temperature for a typical summers day for the DSY reference year and the different climatic scenarios for the 2080's time slice. Note how the morphing proceedure preserves the shape of the diurnal temperature swing, an indication that the underlying weather patterns have not been altered.

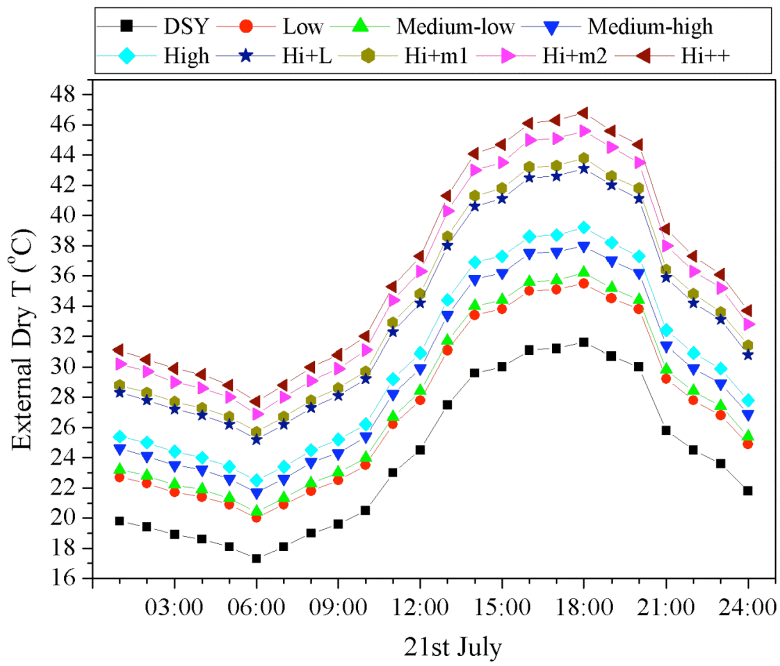

Figure 1. Plot of external Dry T for a typical summer's day for different climatic scenarios.

2. Approach

Over 1000 different combinations of future weather, architecture, ventilation strategy, ventilation type (natural, mechanical and buoyancy driven stack ventilation), thermal mass, glazing, U-value and building use (house, school, apartment, or office) were studied. In addition, more extreme predictions of future weather were included (see Table 1) in order to ensure the results would be still be valid if future climate modelling work or measurements indicate different climatic futures than currently predicted by UKCIP. Thermal simulations of the different architectural designs were performed for the four UKCIP emissions scenarios for the three time slices, 2020's, 2050's and 2080's and also for the four extreme scenarios in the 2080's timeslice. Each building was modelled using an industry-standard dynamic simulation package (IES), which models radiative, conductive and convective heat exchange between building elements and the internal and external environment, and includes dynamic representations of occupancy densities, solar gains, air densities, air flow and heating systems.

Since the morphing procedure does not change the underlying weather patterns, the work was repeated using a series of (un-morphed) historic weather records for various parts of the world that might be considered to represent the possible range of UK future climates, including some extreme changes in the underlying weather. By definition, these demonstrate very different weather patterns and correlations between weather variables.

II. RESULTS

The thermal simulations show that all the buildings studied pass the UK building regulations using the DSY reference year. However, with the use of sequentially more aggressive climate change scenarios increasing numbers of the buildings start to fail. Figure 2 shows how the percentage of (summertime) occupied hours >28°C (a metric used to indicate overheating in the UK building regulations) varies for the different UKCIP02 emissions scenarios at different time slices for a single design of a school. While the school does not overheat using the DSY (1980's time slice) the design fails building regulations from the 2020's onwards for all the emsission scenarios studied, with a peak of over 40% of occupied hours >28°C in the 2080's. This degree of failure is by no means uncharacteristic with some design variants illustration over 90% of occupied hours >28°C by 2080; typically the problem of overheating quickly escalates with the use of more aggressive climate scenarios, these trends are consistent across all the designs of buildings studied.

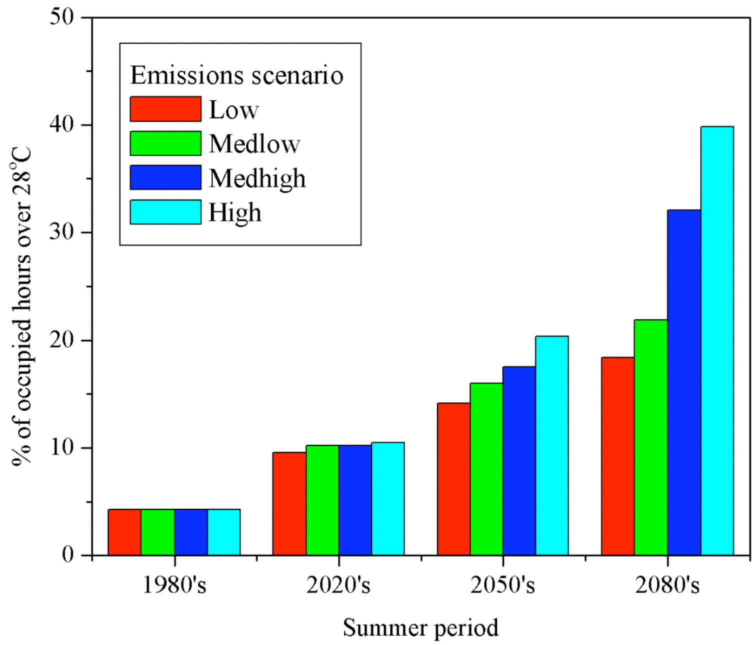

Figure 2: Percentage of occupied hours Over 28°C for different emissions scenarios and time slices.

Clearly the above situaton is unacceptable and will have a profound affect on the thermal comfort experienced within the occupied spaces. As the internal air temperature within the building increases it becomes more difficult for the human body to cool itself. A metric for measuring thermal discomfort is the percentage of people dissatisfied (PPD) (Fanger, 1970). Figure 3 shows the PPD for an open plan working space within an office block sited in London (high emissions scenario 2080's time slice). Each point represents the hourly average air temperature in the space and the resulting PPD for the whole summer period. The graph shows that as the internal air tempeature approaches 37°C all of the building occupants are experiencing thermal discomfort. It is clear from comparison of Table 1 with Figure 3 that under climatic scenarios where the external air temperature is likely to exceed 37°C many people will be experiencing thermal discomfort, unless the building can sucessfully modify the external climate, without resorting to air-conditioning which will exacerbate the problem.

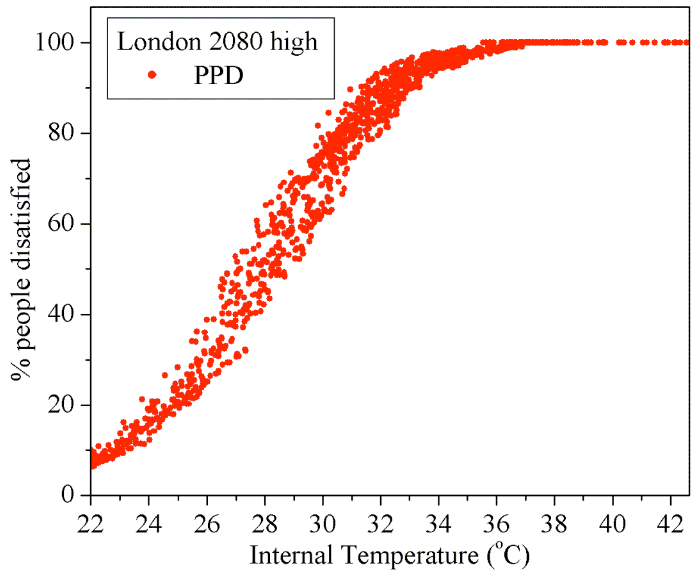

Figure 3: Percentage of People Dissatisfied (PPD) for an open plan office space under high emissions scenario for the 2080's.

3. Climate Change Amplification Coefficients

It is possible to characterise the degree of climate change by the perturbation to the external air-temperature (Dry T) as shown in Table 1 and hence the affect on a given design of building by the change in internal air-temperature. A comparison of external mean or maximal temperatures against the corresponding internal temperature for different perturbations (climate scenarios) yields with a high degree of accuracy a linear relationship. This is suprising since one would assume that the relationship would be a complex sum of the different heat flows within the building structure. Figure 4(a) shows a subset of the results for five buildings for all the climate scenarios studied. We can observe the following (and this is true of all the designs):

- The form of the response to the perturbation of the weather file is always linear, regardless of the architecture, construction, ventilation type or use of building.
- Different buildings demonstrate different gradients ranging from 0.75 to 1.85.
- The intercept of any two regression lines is always at negative values of the perturbation (i.e. to the left of the graph). This implies that any building, which shows a lower mean or maximum internal temperature than another in the current climate will continue to do so for future climates.
- From points 2 and 3 it can be concluded that the response to a perturbation of climate can be characterised solely by the gradient of the regression line—the intercept is not relevant. However, for buildings with large internal gains the internal temperature is higher (the intecept is greater) but the gradient is unaffected (internal gains have no affect on the buildings response to climate change), indicating that comparison of C_T should be restricted to buildings with similar uses and internal gains. The exact relationship between C_T and the intercept requires further investigation.

- Some designs show gradients greater than unity, others less. A value greater than unity indicates that the building amplifies the effects of climate change, while a value less than unity means that it suppresses the effects of climate change.
- There is no advantage in multiple simulations of a building with a range of carbon and climate scenarios. Two simulations are enough to identify the gradient and therefore the response of the building to other scenarios can simply be calculated from the gradient.

Mathematically, we can see that we have two constants (C_{Tmean} and C_{Tmax}) that represent the propensity of any design to overheat given a known perturbation to the current climate:

$$C_{T_{mean}} = \frac{\delta T_{mean}^{internal}}{\delta T_{mean}^{external}} \quad \text{and} \quad C_{T_{max}} = \frac{\delta T_{max}^{internal}}{\delta T_{max}^{external}},$$

where *mean* and *max* refer to the mean or maximum temperature observed either in the weather file (*external*) or within the building (*internal*). We term such constants *climate change amplification coefficients* (C_T), and presumably other such descriptors could be identified (for example changes in cooling demand for air conditioned buildings). The correlation coefficient (R^2) of C_T exceeds 0.997 for all the buildings studied.

C_{Tmean} and C_{Tmax} fully describe the response of the maximum and mean temperature of any design to a changing climate and the existence of such coefficients of proportionality demonstrates that the concern expressed in the introduction about the potential complexity of the response function is invalid. We believe that such coefficients are highly suitable for describing the response and relative benefits of a series of design alternatives. In essence they indicate the degree of amplification (or suppression) the architecture of a building is capable of. So if, for example, C_{Tmean} = 1.5 for a building, a prediction of 2°C rise in mean summertime temperature from a climate model implies with a high degree of accuracy a 3°C rise in mean summertime internal temperature. Because these two coefficients appear to be able to take values either side of unity, it is tempting to describe buildings that have values less than one, as *resilient*, and those with values greater than one as *non-resilient*. However, this simple binary classification ignores the potentially serious consequences of higher indoor temperature for vulnerable groups, where even a mild increase in temperature can be fatal if it is sustained over several days with a minimal diurnal cycle.

It might be thought that one possible explanation for the linear response can be found in the form of the perturbations used in the morphing process, detailed in Belcher (2005). However, as mentioned above, another way to produce a time series indicative of future weather is to use historic weather from a location that has a climate similar to that predicted for the future climate in the location of interest. In general, such time series diverge far more from the historic weather in the location of interest and cannot be represented by shift and stretch functions. A subset of the buildings was simulated with historic weather files from other locations, the results for one building are summarised in Figure 4(b). Again, we see that such perturbations still engender a linear response, although with a lower correlation coefficient.

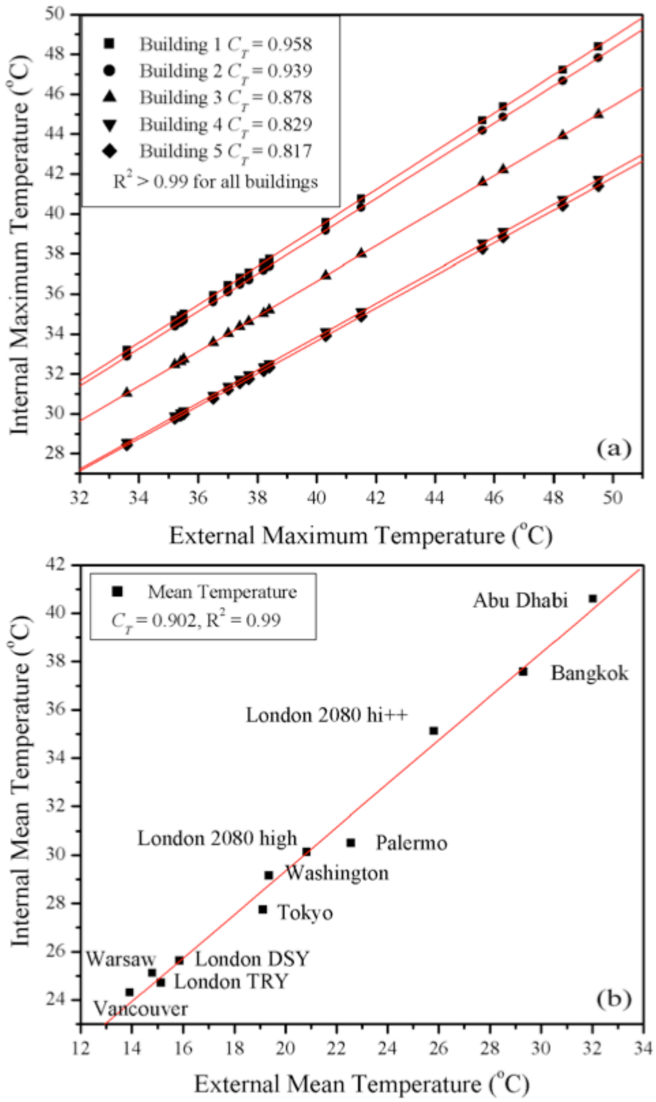

Figure 4: (a) Plot of the response of five buildings to different climate change scenarios described by their perturbations to internal and external maximum air temperatures. (b) Plot of the response a building to different climates described by their perturbations to internal and external mean air temperatures.

4. Case-study

Using a highly detailed thermal model (Figure 5 inset) of a newly built school in the UK which overheats and demonstrated low thermal comfort upon completion we show how the use of climate change amplification coefficients could have produced a building that not only fares better in the current climate but also under the effects of predicted future climate change.

Typically the DSY reference year used to model a building for overheating analysis is the 3rd hottest observed summer period between 1983 and 2004. Modelling the building as constructed using the entire base set of observed summers in the same period shows that, while the referece year is on average the 3rd hottest in terms of external air temperature is the 6th hottest in terms of mean internal air temperature and hours of overheating (>28°C), falling to 8th if 2005/06 are included. This is not suprising since the internal temperature of a building is dependant on other weather variables in addition to air temperature. Thus, while the modelled design just passes the building regulations, a good proportion of the observed weather years from which the reference year is chosen cause the building to fail. It is clear that the DSY reference year is outdated and does not take into count recent changes in climate, hence it is unsupprising that the building overheats in the current climate and demonstrates low thermal comfort. Calculation of the climate change amplification coefficient for different design variations would have allowed an estimate of how the building would respond to different climatic conditions without having to run a large number of simulations.

A climate change amplification coefficient C_T can be calculated using only two simulations of a building (we have used four in this case study for clarity) and can give an estimate of how that design will behave for any given amount of climate change irrespective of weather patterns. This means that the outdated snapshot of weather and climate represented by the reference year can be replaced by a distribution of possible climatic scenarios by performing a single extra simulation. By altering design features and ventilation strategies of the building model to minimise C_T it is possible to create a building that should perform well for many years to come. Using the model of the school as an example several different variations of the design were simulated and C_T calculated. The value of C_T for the school as constructed is 1.031 (0.761) for the mean (maximum) internal air temperature (averaged across all rooms in the school). By increasing the admittance of some of the internal surfaces and altering the ventilation strategy to include night cooling to restore the coolth of the internal structure it is possible to reduce the values of C_T to 1.009 (0.749) for mean (maximum) internal temperature (C_{Tmax} is the line gradient in Figure 5). While these reductions may not seem large this translates to a reduction in the predicted mean (maximum) internal temperature of the school of 1.5 °C (2.9 °C) and a reduction of 100 hours of overheating by 2020 (Figure 5), what is more the building would still pass the building regulations in the 2020's time slice. Indicating that if the building had been constructed with these modifications then it would not currently overheat and would still be usable for many years to come.

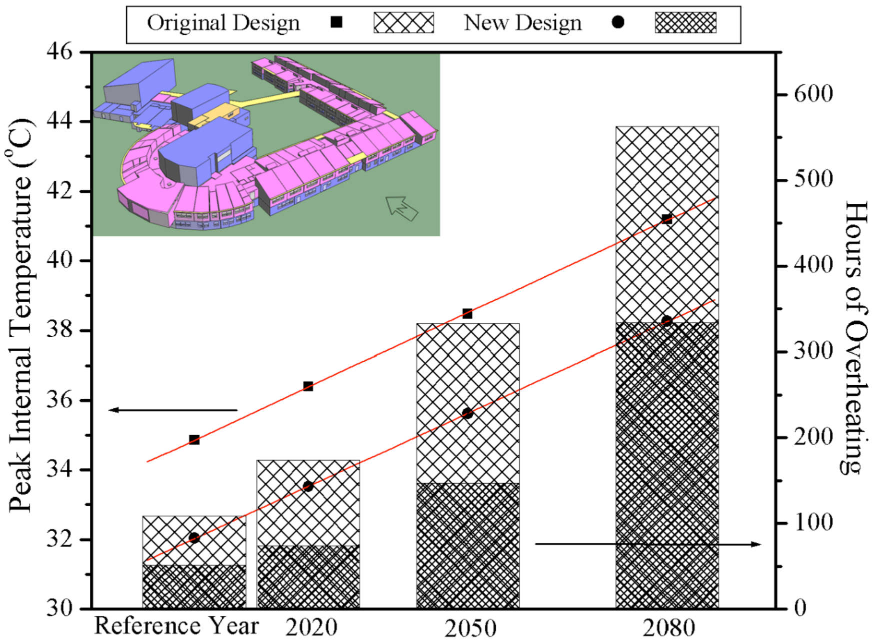

Figure 5: Plot of peak internal temperature and hours of overheating (both averaged over the entire school) for different time slices under the high emissions scenario. Inset: a rendering of the thermal model of the school used.

III. CONCLUSIONS

Driven by questions of increased morbidity and mortality of vulnerable groups particularly in mid-latitude cities as the climate warms, the general form of the response of the internal environment within buildings to perturbations in climate has been studied. The response, as measured by the change in mean, or maximum, internal summertime temperature, to a change in mean or maximum external temperature, would appear to be linear, regardless of whether the perturbations are created by simple mathematical transformations of historic weather, or by the use of historic weather from other, warmer, cities.

We have termed the resultant constants of proportionality *climate change amplification coefficients* (C_T), and suggest that the estimation of these for new or existing buildings will allow more rapid thermal modelling of buildings with respect to climate change, the design of more resilient buildings, cost-benefit analysis of refurbishment options and the rational assembly of at-risk registers of building occupants. Furthermore we have shown how minimising the climate change amplification coefficient C_T during the design process can be used to adapt a building to the affects of climate change, reducing overheating and improving thermal comfort.

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