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The Response of the Built Environment to a Changing Climate

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Abstract

In August 2003, 14,800 heat-related deaths occurred in Paris [1] during what is considered the warmest summer since at least 1500 [2–5]. These deaths resulted not only from unusually high peak temperatures and a reduction in the diurnal temperature swing, but also from a failure of buildings to successfully modify the external environment. It has been estimated [6] that that by the 2040s, a 2003-type summer is predicted to be average within Europe. Clearly this will have a great impact on morbidity and mortality and produce challenges for emergency services [7]. The effects of climate change on the internal environment are not well known and are the subject of much current research [8]. For building scientists and emergency planners, there is the need to know the general form of the relationship between increases in external temperature due to climate change and increases in internal temperatures. Here we show that the relationship is linear, and that differing architectures give rise to differing constants of proportionality. This is a surprising result as it had been assumed that, given the complexity of the heat flows within large structures, no simple relationship would exist [9]. We term these constants of proportionality *climate change amplification coefficients*. These coefficients fully describe the change in the internal environment of an architecture given a seasonal or annual change in external climate and can be used to judge the resilience to climate change of a particular structure. The estimation and use of these coefficients for new or existing buildings will allow: the design of more resilient buildings adapted to a changing climate, cost-benefit analysis of refurbishment options and the rational assembly of at-risk registers of vulnerable building occupants.

Keywords: adaptation, climate change, building, overheating, temperature.

Introduction

Predictions of the world's climate point to an increasingly warmer world, with greater warming across land and away from the equator [10]. Predictions contained in the IPCC's fourth assessment report indicate mid-latitude mean temperature rises over land of ~4°C (under the A1FI scenario) [10]. However, recent research [11] shows that current emission trends imply that the actual temperature increase could be far higher than the A1FI scenario predicts. This implies that several highly populated regions not used to high temperatures will be exposed to a very different summertime experience. As the events in Paris in 2003 showed, temperature rises and reductions in the diurnal cycle within the built environment can have life-threatening consequences and require a substantial response from emergency services [12]. 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 [6] and this will clearly have a great impact on the energy consumption of air condition spaces and the thermal comfort within non-conditioned ones.

Heat stoke was first recognised by the Romans in 24BC but it was not until 1946 that a true understanding of the extent of the damage it can cause to an individual was formed [13]. In order 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 ventilated, non air conditioned, buildings to changes to summertime temperatures. Given a 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 material, 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 to 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.

Prediction of Future Weather

Given statements of future climate by the IPCC and others [14] 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 *et al* [15].

Belcher *et al* [15] 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 [16]). This methodology is termed 'morphing' (see Method).

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 the future weather times series created using morphing and used in this work.

Table 1. Values of min, max and mean dry bulb temperature (Dry T) and deviation of the mean from the third warmest summer over the period 1983 to 2004 (termed DSY) all for London, UK. Historic TRY refers to a typical year assembled from data spanning the period 1983 to 2004. Low, medium-low, medium-high and high refer to morphed weather based on the DSY weather file using coefficients produced for London by the UK climates impacts programme [16]. Hi+L, Hi+m1, Hi+m2 and Hi++ refer to morphed weather created by applying the morphing twice to the DSY weather file. The values shown are for the summer-period April to September.

Scenario	Min Dry T(°C)	Max Dry T (°C)	Mean Dry T (°C)	δ Mean T (°C)
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

Approach

Over 400 different combinations of future weather, architecture, ventilation strategy, thermal mass, glazing, U-value and building use (house, school, apartment, or office) were studied. This makes the extent of the design space investigated far greater than that considered in other works [9]. 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. Since the morphing procedure does not change the underlying weather patterns, several scenarios were included that represent complete changes in the weather patterns

and particularly the correlations between temperature and humidity. Each building was modelled within the IES [17] dynamic simulation environment 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. Table 2 gives details of the range of architectural and constructional parameters studied. All buildings were assumed to be sited in London.

Table 2. Range of architectural and constructional parameters included in the study.

Parameter	Range
Thermal capacity	10 KJ/m^{2}K $\rightarrow$ 230 KJ/m^{2}K
Fabric thermal resistance	0.11 W/m^{2}K $\rightarrow$ 0.44 W/m^{2}K
Glazed fraction	14% $\rightarrow$ 60% of main facade
Building size	135 m^2 $\rightarrow$ 2814 m^2
Orientation of main facade	0°, 90°, 180° 225° and 270° degrees east of north
Window opening	10% $\rightarrow$ 75%
Infiltration rate	0.1 ach^{-1} $\rightarrow$ 1 ach^{-1}

Results

Figure 1 shows a subset of the results for five of the buildings. Figure 2 shows the results for all the buildings characterised by the response of a building to a change in the climate. We can observe the following (and this is true of all the designs):

1. The form of the response to the perturbation of the weather file is always linear, regardless of the architecture, construction or use of building.

2. Different buildings demonstrate different gradients.

3. 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.

4. From points 2 and 3 it can be concluded that the response can be characterised solely by the gradient of the regression line—the intercept is not relevant.

5. 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.

6. 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.

lines $T_{max}^{internal} = T_0 + C_{Tmax}\delta T_{external}$, showing the linearity of the response and therefore the potential for fully describing the response of any building with a single parameter.

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 given by equations 1 to 3 (see Method). As mentioned above, another way to produce a time series 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 can not be represented by shift and stretch functions. A subset of the buildings were simulated with historic weather files from other locations, the results for one building are summarised in Figure 3. Again, we see that such perturbations engender a linear response, although with a lower correlation coefficient.

Summary and 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 weather 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.

Method

The basic underlying process for the morphing of the weather files consists of three different algorithms depending on the nature of the parameter to be morphed.

(1) A 'shift' of a current hourly weather data parameter by adding the predicted absolute monthly mean change:

eqn. 1
$$x = x_0 + \Delta x_m,$$

where x is the future climate parameter, x_0 the original present-day parameter and Δx_m the absolute monthly change. This equation is, for example, used for adjusting atmospheric pressure.

(2) A 'stretch' of an hourly weather data parameter by scaling it using the predicted relative monthly mean change:

eqn. 2
$$x = \alpha_m x_0,$$

where α_m is the fractional monthly change. This is used for example to morph present-day wind speed values.

(3) A combination of a 'shift' and a 'stretch' for current hourly weather data. In this method a current hourly weather data parameter is shifted by adding the predicted absolute monthly mean change and stretched by the monthly diurnal variation of this parameter:

eqn. 3 $\qquad x = x_0 + \Delta x_m + \alpha_m(x_0 - \langle x_0 \rangle_m) = \langle x_0 \rangle_m + \Delta x_m + (1 + \alpha_m)(x_0 - \langle x_0 \rangle_m),$

where $\langle x_0 \rangle_m$ is the monthly mean related to the variable x_0 and α_m is the ratio of the monthly variances of Δx_m and x_0. This method is for example used to adjust the present-day air temperature. It uses predictions for the monthly change in the diurnal mean, minimum and maximum dry bulb temperature in order to integrate predicted variations of the diurnal cycle.

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Figure 1. Results for five design varients of a typical new build house together with linear regression lines $T_{max}^{internal} = T_0 + C_{Tmax}\delta T_{external}$, showing the linearity of the response and therefore the potential for fully describing the response of any building with a single parameter.

Figure 2. Box and whiskers plot of the amplification coefficient for all the buildings studied. The square represents the mean and the box represents the 25-75 percentile range. The whiskers represent one standard deviation away from the mean and the crosses the max and min values.

Figure 3. Change in mean internal temperature for one of the buildings in the study as a function of change in mean external temperature (with respect to the London DSY) given by a series of weather files from around the world: the response would appear to be approximately linear. The correlation coefficient is still high for this data with $R^2 > 0.985$.
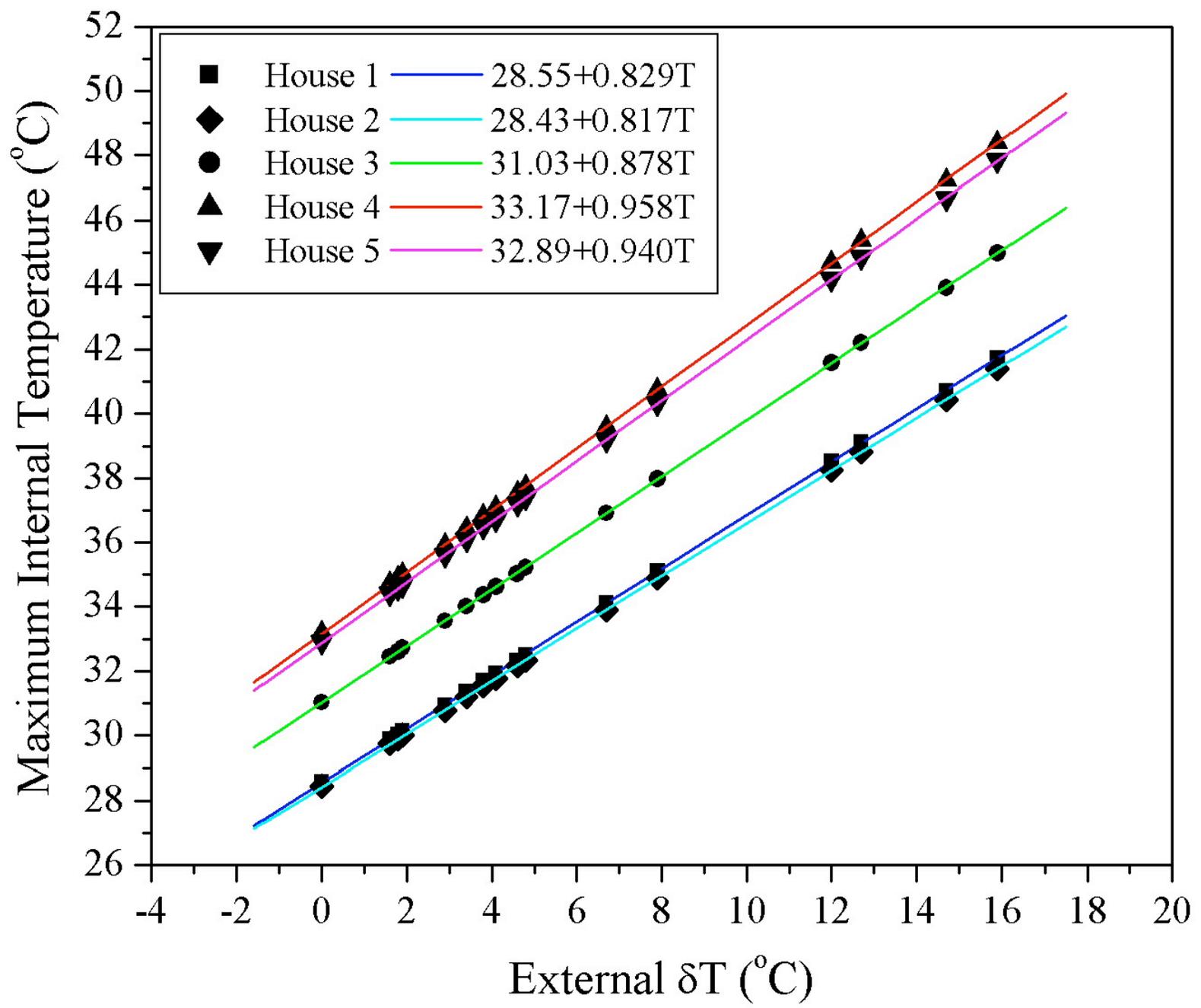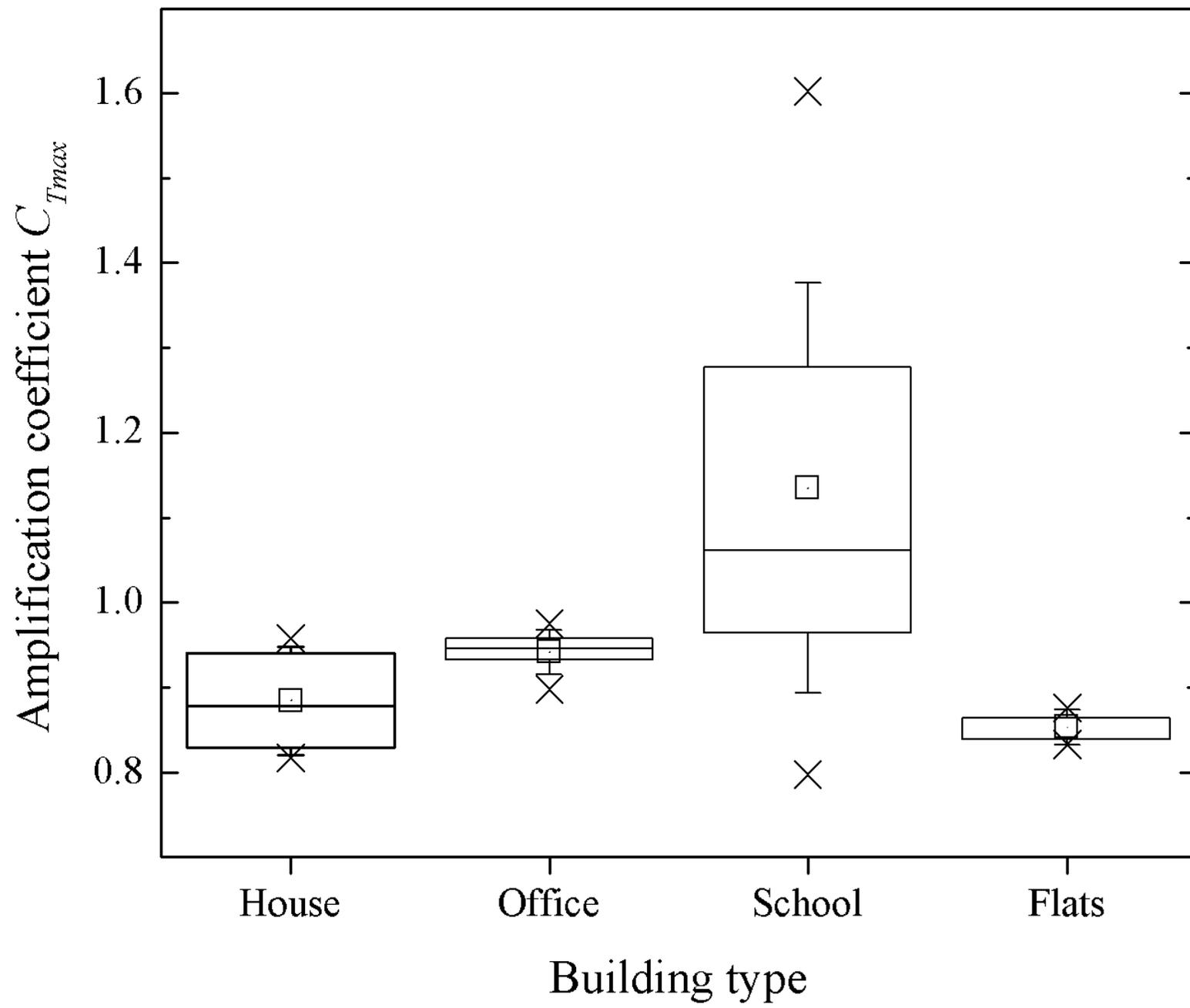
Figure1

Figure2

Figure3