Centre for Energy and the Environment
Tel. (01392) 264144
Fax. (01392) 264143
Website http://www.ex.ac.uk/cee/
E-mail d.a.coley@ex.ac.uk

Climate Change, Thermal Comfort and Building Design

David Coley and Tristan Kershaw Nov 2008, CEE Report 121

Presented at *Thermal Comfort for Building Occupants*, CIBSE, London, 18th November 2008

Abstract
The world's climate is changing. Here we review the level of historic changes, look at one prediction of future climate and investigate what impact this would have on a typical school built to the current building regulations. We then study how the environment within a building is likely to change for a range of future predictions of climate, including some more extreme than commonly considered. From this work it would appear that the first derivative of the change in maximum (or mean) internal temperature with respect to changes in maximum (or mean) external temperature is a constant across all scenarios. We have termed this constant a *climate change resilience coefficient,* C_{Tmax}, and believe it likely that the concept is a general one that can be used to asses the resilience of any design. In addition, we have found that the value of C_{Tmax} displayed by a design is maintained even if the UK were to experience radical climate change that led to very different weather patterns. By extending this approach to comfort we have found that the idea of a resilience coefficient is still valid when discussing predicted mean vote.

Introduction
In this paper we present some thoughts from several sources on the degree of climate change the UK may face over the lifetime of new buildings, the impact this might have on schools and introduce a metric for the resilience of a building to climate change.

Past Climate
The Earth has experienced a wide variety of climates through its 4.5 billion years history. Figure 1a details the last 500 million years and Figure 1b the last 65 million (both sets of data should be considered approximate). We see that there has been great variability in the planets climate over this time period. This is hardly surprising as during these periods the composition of the atmosphere, volcanic activity, the location of the continents, the number, diversity and form of living creatures, and the output of the sun have changed greatly. More recently (Figure 2), we experienced a series of alternating ice ages and inter-glacials. With ice ages being the more common state for the planet with the system seeming to flip-flop between these two states rather than simply varying between the bounds. In addition, we now seem to be artificially warming the world's climate during a warm period. There are therefore concerns that the planet may leap to a, as yet unknown, third state not experienced for at least 500,000 years.

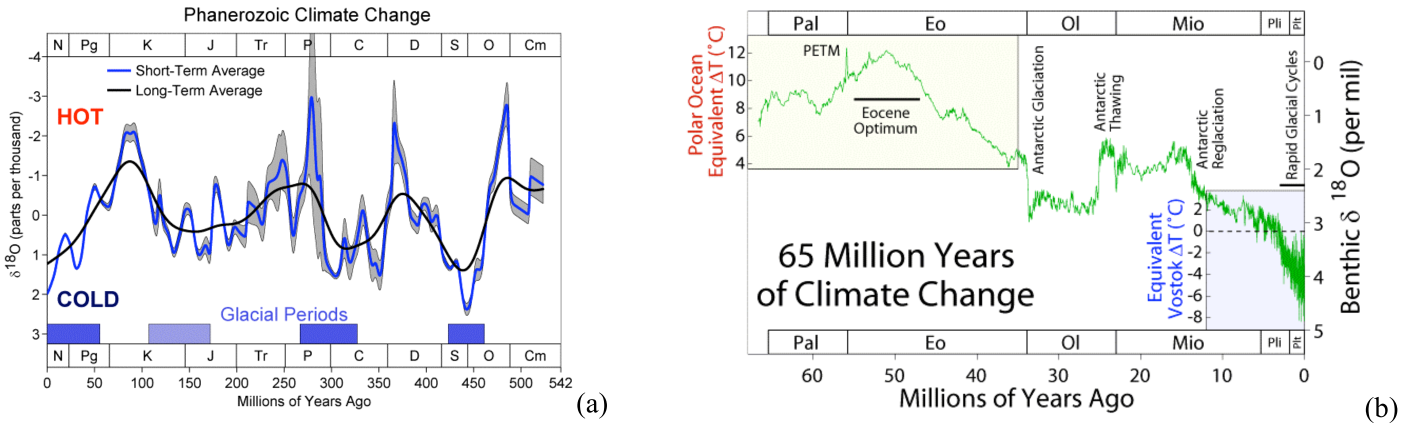

Figure 1. (a) the last 500 million years, (b) the last 65 million years (the latter shows the Earth's temperature since the extinction of the dinosaurs about 65 million years ago). The figures show the long-term evolution of oxygen isotope ratios as measured in fossils, reported by Veizer et al. [VEI99]. Such ratios reflect both the local temperature at the site of deposition and global changes associated with the extent of permanent continental glaciation. As such, relative changes in oxygen isotope ratios can be interpreted as rough changes in climate. Quantitative conversion between this data and direct temperature changes is a complicated process subject to many systematic uncertainties, however it is estimated that each 1 part per thousand change in $\delta^{18}O$ represents roughly a 1.5-2 °C change in tropical sea surface temperatures (Veizer et al. 2000).

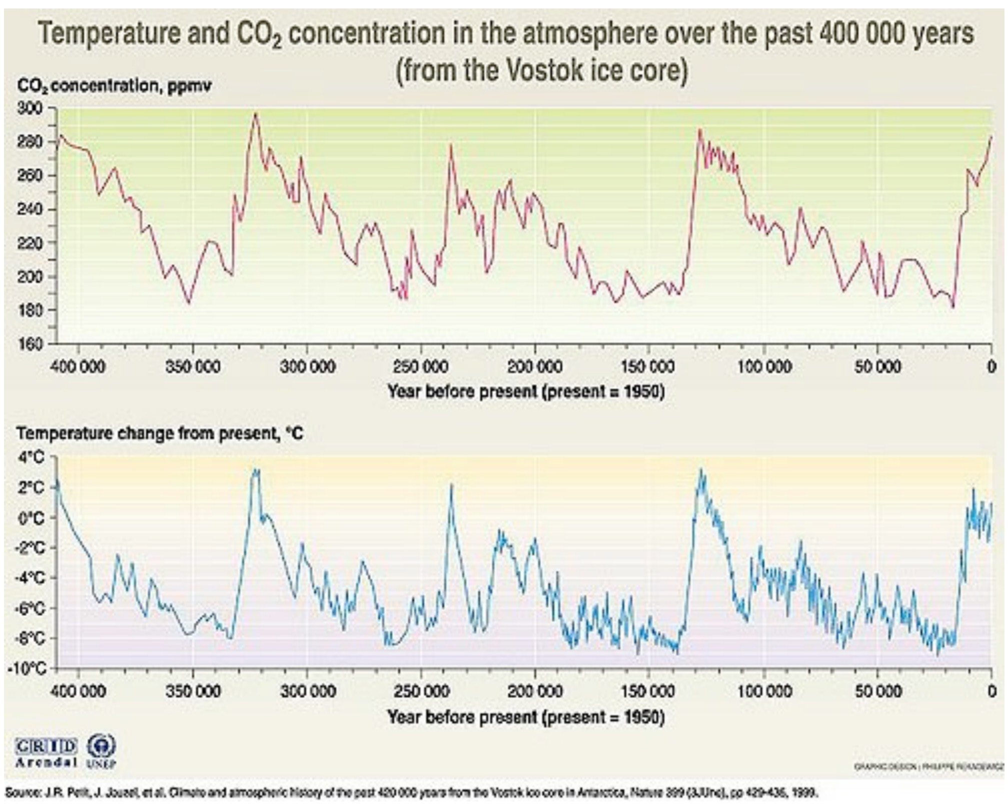

Figure 2. The last 500 thousand years with the regular pulse of ice ages shown (from IPCC).

Although the speed of change between warm and cool periods is the subject of ongoing research, it would appear that at least some of the historic swings in global and regional temperature were extremely rapid (and possibly driven by tripping points that caused changes in the global sea currents, for example the gulf stream). Figure 3 shows the last 50,000 years. Prominent in this graph are the seemingly regular spikes in ^{18}O levels, marked with letters and numbers. The spikes indicate excursions of warmer weather when it is believed that the climate of Greenland changed rapidly - by as much as 8-16 deg. C in as little as 40 years. These anomalous warm phases are called Dansgaard-Oeschger events. This gives us some concern that during the lifetime of buildings climate change may be far more extreme and rapid that typically considered.

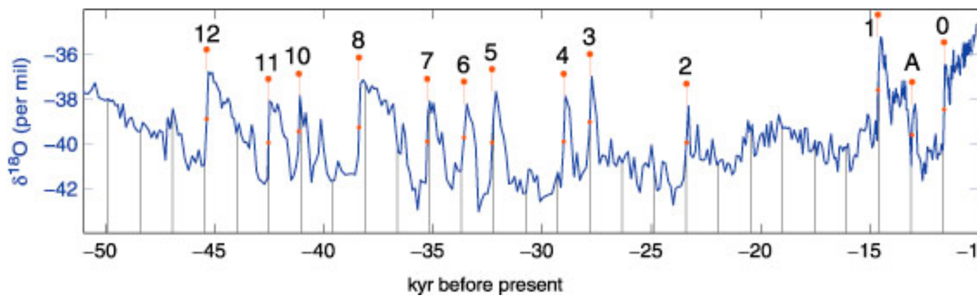

Figure 3. Dansgaard-Oeschger warm events as seen in the GISP2 ice record. The D-O events are defined as a >2 unit rise in the ratio of ^{18}O to ^{16}O (vertical axis) occurring in less than 200 years. The often mentioned Younger-Dryas cool event is the dip in ratio values after the 'A' warm event. [RAH03].

Current Climate

The UK's climate has changed quite a bit over the last forty years, as demonstrated by maps produced by the UK's Climate Change Impacts Program (UKCIP) (Figures 4 and 5). The change over this period is possible greater than some suspect.

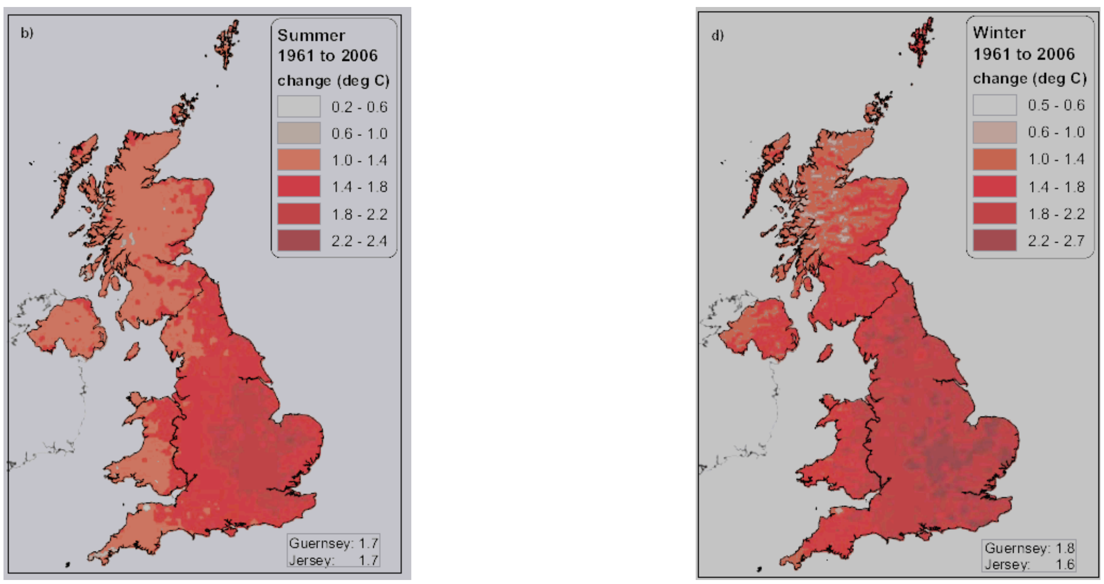

Figure 4. Change in mean daily temperature [UKCIP1].

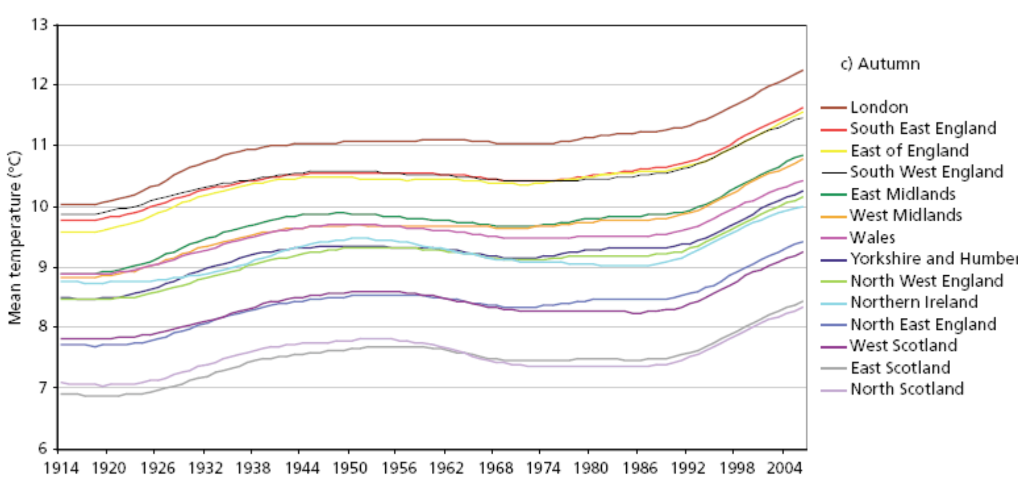

Figure 5 Change in mean daily temperature [UKCIP1]

Future Climate

The Hadley centre and UKCIP have modelled the future of the UK's climate using large three-dimensional physical models of the Earth's atmosphere and oceans. One of the main inputs for these models is a time series of future world anthropogenic greenhouse gas emissions. This time series is difficult to estimate, and it would appear that we are placing far more carbon dioxide into the atmosphere than was assumed by the models. Another problem with this modelling work is that they find it difficult to estimate the rate of change in the extent of ice, and this means that changes in the albedo of the planet have not been correctly included. Another problem is with feedback processes such as the release of methane from permafrost as the world warms and it melts. This would in turn lead to more warming and the establishment of a positive feedback loop. Again this is not covered by such modelling work. Because of this Figures 6, 7 and 8 need to be seen as conservative. However, even without such adjustments, it is clear that we can expect a much warmer situation in the UK even if the world radically reduces its emissions of greenhouse gases (the lower emissions scenario in Figure 6). We also see that the situation is predicted to be different in different regions with greater changes over land than the oceans. This regional diversity needs to be remembered when considering mean global temperature rises often headlined in the press.

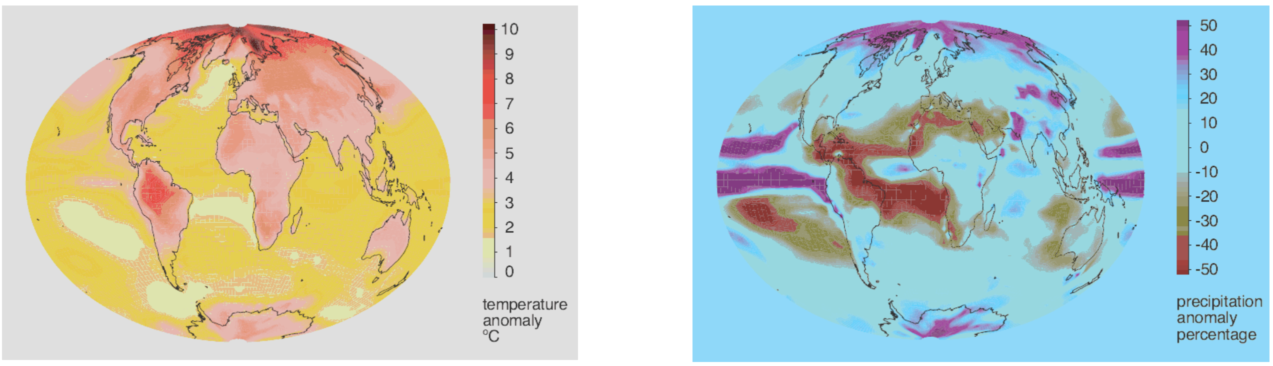

Figure 6. Change in annual average temperature (left) and precipitation (right) for the 2080s period, relative to 1961-1990, for the HadCM3 ensemble-average model under an A2 forcing scenario.

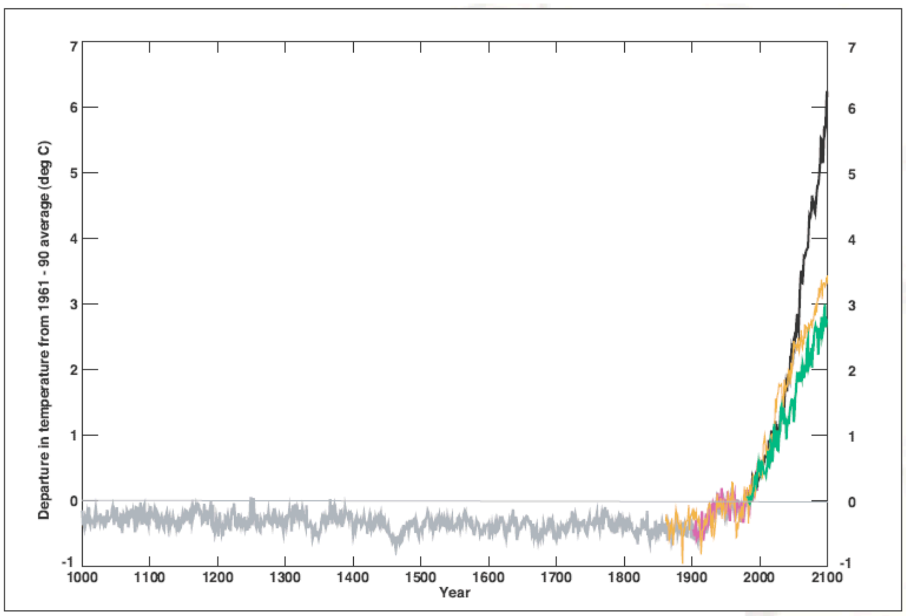

Figure 7: Past and future temperature for the Northern Hemisphere expressed as anomalies from a 1961-1990 average. Grey = reconstructed from environmental data for 1000 to 1980; pink = observed from thermometers for 1901 to 1999; orange = a single model simulation for 1860 to 2100 with "observed" natural and anthropogenic forcings to 2000 and then a mid-range emissions scenario from 2000 to 2100; green = a single model simulation for 1981 to 2100 using a low emissions scenario; black = a single model simulation for 1981 to 2100 using a high emissions scenario. All simulations were carried out using the HadCM3 model. [UKCIP02].

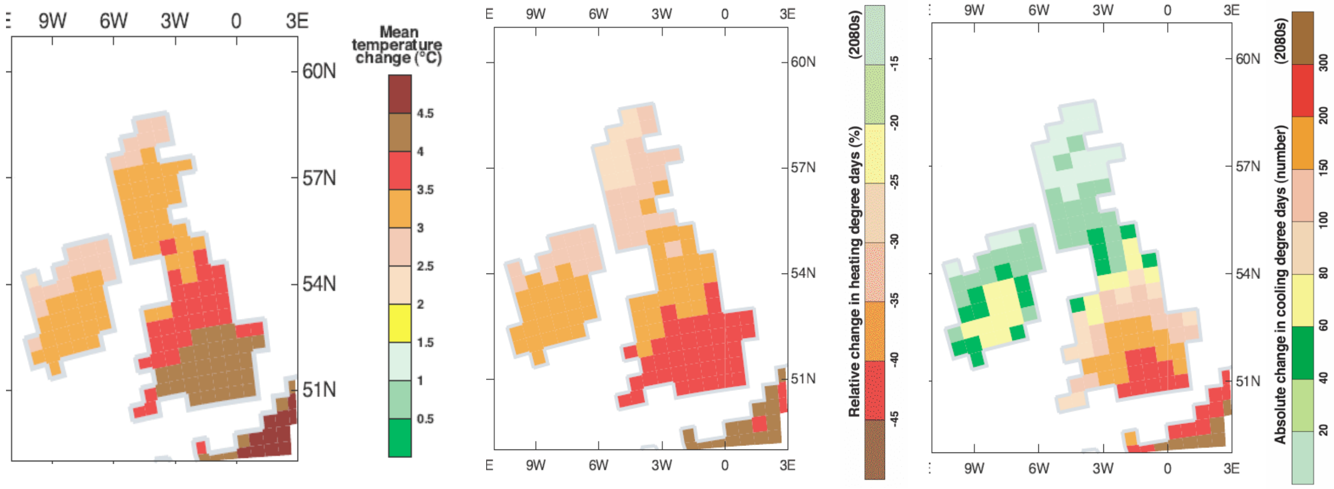

Figure 8. (Left) change in average annual temperature (with respect to the model-simulated 1961-1990 climate) for thirty-year periods centered on the 2080s for the UKCIP high emissions scenario. (Middle) Per cent change by the 2080s in the average number of heating "degree days" with respect to the model-simulated 1961-1990 baseline period. (Right) change by the 2080s in the average number of cooling "degree days" with respect to the 1961-1990 baseline period. [UKCIP02].

Impact on a Typical School

Although currently there is no requirement for building designers to take climate change into account, given the lifetime of most buildings and the predictions by UKCIP and others of the future UK climate, it would seem sensible to have some understanding of how a building is likely to be affected by climate change. Given that we often find little margin between the predicted internal environment and the requirements of the building bulletins for schools it seemed sensible to run a test case on a single real school and a single future weather file.

There are several ways to create weather files representing future climate, for instance using recorded historical data for locations whose current climate matches that predicted for the UK. This has the downside that certain weather variables such as hours of daylight, will not be correct. 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* [BEL05].

Based on the UKCIP02 data output, Belcher *et al* have developed a methodology for transforming CIBSE TRY and DSY weather files into future weather years representative of the different climate change scenarios. Hourly CIBSE weather data for the current climate is adjusted with the monthly climate change prediction values of the UKCIP02 emission scenario datasets. This methodology is termed 'morphing'. The basic underlying process for the morphing of the weather files consists of three different algorithms depending on the nature of the parameter to morphed.

(1) A 'shift' of a current hourly weather data parameter by adding the UKCIP02 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 according to the UKCIP02 scenarios. This method is, for example, used for adjusting atmospheric pressure.

(2) A 'stretch' of an hourly weather data parameter by scaling it using the UKCIP02 predicted relative monthly mean change:

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

where α_m is the fractional monthly change according to the UKCIP02 scenarios. 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 UKCIP02 predicted absolute monthly mean change and stretched by the monthly diurnal variation of this parameter:

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

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 dry bulb temperature (Dry T). It uses the UKCIP02 scenario predictions for the monthly change of the diurnal mean, minimum and maximum Dry T in order to integrate predicted variations of the diurnal cycle.

The morphing process presented above has the advantages 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 preserves any failings in the basic TRY and DSY approaches and doesn't allow for fundamental changes in weather.

Figure 9 shows the air temperature predicted for a single summer week within a single classroom from a whole building simulation (the details of which are not important to this work, but the school is typical in most regards). We see that the run with the new weather file for 2080 (produced using the morphing method just described) results in a markedly different environment and that most would consider it unacceptable. We also see that the difference between the internal temperatures is slightly greater than that simply given by the difference between the external temperatures in the two weather files (Figure 10)—this an worrying indication that buildings have the potential to magnify changes to our climate.

Table 1 shows summary data for the whole summer period for the two runs. We see that the 2080 weather results in a design that is nowhere near achieving the requirements of Building Bulletin 101 (the document that sets limits for overheating). It is clear that there are grounds for concern and that it might be wise to ensure future modelling of buildings includes some work done with weather files that represent the likely climate over the life-time of the building.

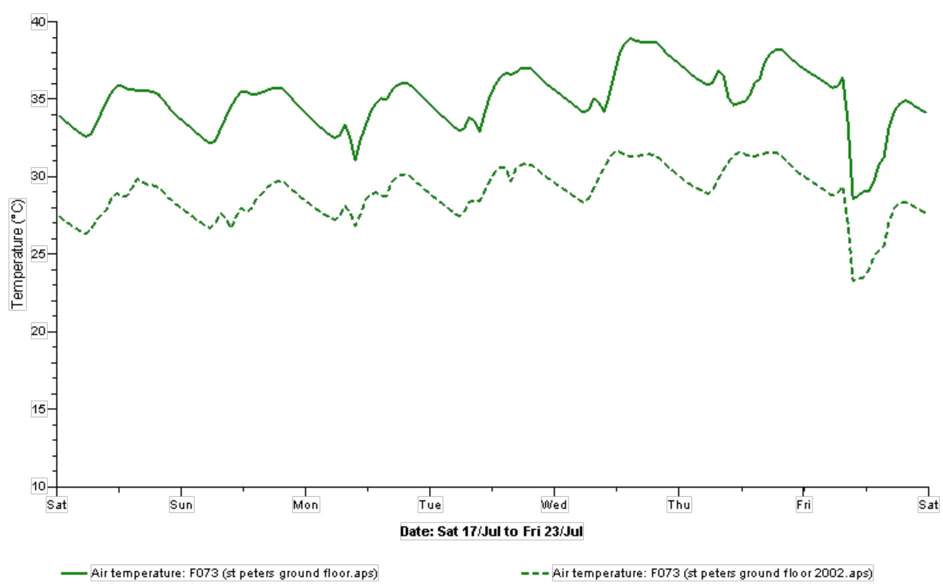

Figure 9. Results for a single classroom during a summer week. Temperatures near 40°C are seen in the simulation using 2080 weather (solid line) and that this is approximately 7.5°C warmer that that using the current design summer year (dashed line).

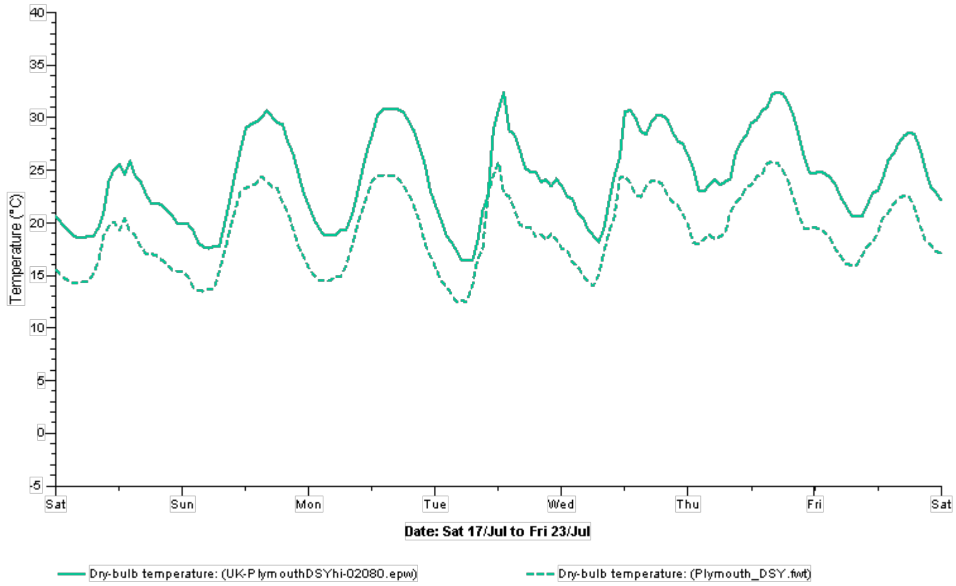

Figure 10. The external temperatures during the same week as Figure 9.

Weather	Hours over 28°C	Maximum temperature (°C)
Current DSY	91	31
2080 DSY	307	39
BB101 requirement	Less than 120	32

Table 1. Summary data, in line with the requirements of BB101. (Occupied summer period.)

Other Buildings and More Extreme Climate Change

Having shown (as others have) that building occupants are likely to suffer as the climate changes, it would seem sensible to try and quantify the form of the sensitivity of all building or designs to a changing climate. At first this might seem difficult as it might be expected that the sensitivity of a design is likely to be a non-linear function of changes to climate. So, one design might be more sensitive to changes in sunlight, another to changes in air temperature. Also, that this change might be complex, with, for example, a building showing very little sensitivity to a small change in the climate but than an increasing response as the change becomes more extreme.

In order to see if this difficulty is well founded, weather files representative of the possible weather between 2020 and 2080 were created and again applied to a thermal model of a school. Unlike other work done on this subject, 28 variants of the basic design were studied in order to see if a consistent message would arise regardless of thermal mass, ventilation, glazed fraction and U-value. In addition, more extreme climate change scenarios were studied than is usual and a sensitivity analysis carried out with regard to the main climatic driving forces. In total 252 building/weather scenario combinations were studied. The results show the first indications that changes in the internal environment within buildings will follow linear trends under a changing climate (i.e. in direct proportion to the amount of climate change), and that the constant of proportionality that this implies (which we term the *climate change resilience coefficient*) is different for different buildings and can be used to characterise the inherent level of robustness of a design to a changing climate. This modelling and the results obtained are for naturally ventilated and cooled buildings. For mechanically cooled buildings the situation may well be different, with the indoor environment showing little change until the point where the cooling system can no longer keep pace with the increasing external temperatures.

UKCIP02 only includes the results of modelling based on four emission scenarios, none of which could be considered extreme, and as has been suggested above, various physical and feedback processes missing in the climate modelling UKCIP02 relies upon might lead to greater or more rapid changes in the UK's climate. Buildings last a long time and repeated incremental alterations can be expensive. It therefore seems sensible to study the possible implication of more extreme climate change as soon as possible, but how? Due to the lack of a better alternative, it was decided to create alternative, extreme, weather time series by either simply adding an integer number of degrees centigrade to the time-series of external temperatures prior to morphing (scenarios high +1,+3,+5), or by running the morphing algorithm twice (scenario high++). Whilst crude and easily open to criticism, it was hoped that this approach would at least allow us to consider the degree of concern the construction industry should have for the possibility of more extreme climate change.

Table 2 gives descriptive statistics of the morphed weather files and the current TRY and DSY for London over the summer period.

Table 2. Values of min, max and mean Dry T and deviation of the mean from the DSY over the summer period for the different scenarios. Note that the high++ scenario has an almost identical mean to the high +5 scenario.

Scenario	**Min Dry T (°C)**	**Max Dry T (°C)**	**Mean Dry T (°C)**	**δ Mean T (°C)**
TRY	1.10	30.10	14.71	-1.14
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
High +1	4.00	42.50	21.83	5.98
High +3	6.00	44.50	23.83	7.98
High +5	8.00	46.50	25.83	9.98
High ++	6.00	49.50	25.81	9.96

Figure 11 shows a plot of the increase in maximum internal temperature for one of the classrooms against increase in maximum external Dry T for the different scenarios studied with respect to the DSY for four building variants, a light and heavy thermal mass construction and their super insulated equivalents (the buildings are the same in every other way). The plot shows that for a given increase in the external temperature due to climate change the light weight building's internal temperature increases more than the heavy weight equivalents. Super insulation of the building also slightly decreases the extent of the internal temperature increase. Upon closer inspection of Figure 11 the UKCIP02 future scenarios seem to follow an exact linear trend, whereas the custom high +1,+3,+5 scenarios deviate from this trend slightly and appear to underestimate the increase in internal temperature. The high++ scenario however returns to the linear trend of the UKCIP02 scenarios, indicating that it may be a more realistic representation of extreme climate change in buildings.

The existence of such a simple linear trend was unexpected given the complexity of the building/occupant/ventilation/weather model. In essence, we can conclude that internal environments will evolve in a linear way with growing external temperatures even under extreme climate change, i.e. that:

$$\frac{d\delta T_{\mathrm{max,internal}}}{d\delta T_{\mathrm{max,external}}} = C_{T_{\mathrm{max}}}$$

where $C_{T\mathrm{max}}$ is a constant (which we term the *climate change resilience coefficient*) over all climate change scenarios, but varies for different constructions, and presumably differing architectures. (A similar equation is found for mean summertime temperature.)

This indicates that a useful way to describe the robustness of a design under a changing climate is to estimate $C_{T\mathrm{max}}$ for the design and compare it to known values of other buildings. In practice we find that C_{Tmax} (or C_{Tmean}) can be less than or greater than unity. Thus a particular design either suppresses, exacerbates the impact of climate change.

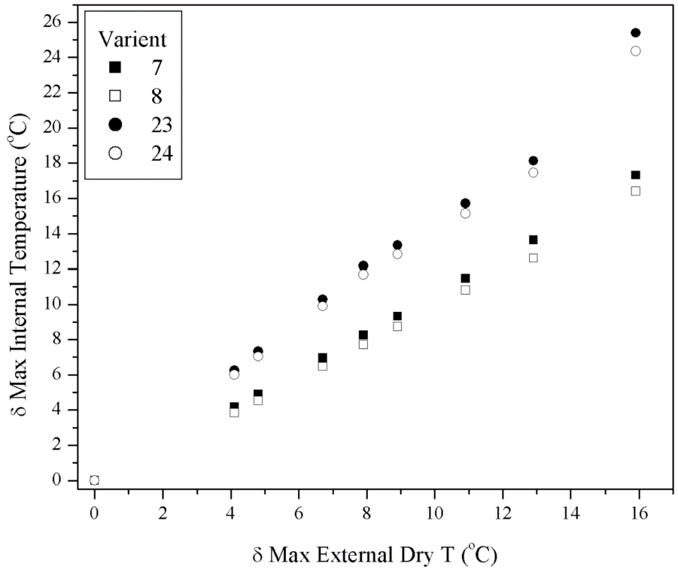

Figure 11. Plot of internal maximum temperature increase for a classroom versus external maximum temperature increase for the different 2080 climate scenarios with respect to the DSY for a light (circles) and heavy (squares) weight building and their super insulated equivalents (open symbols).

Other Climates

One possible reason for the linear trend shown in Figure 11 is simply a reflection of the simplicity of the morphing procedure used—i.e. the type of weather is not changing between scenarios. The mean and variance of the various weather parameters is changing but fundamentally the weather systems involved are the same. What happens if climate change leads to fundamentally different weather across the UK? For example the dominance of high pressure during the summer and therefore a more continental weather.

Figure 12 shows the similar data as Figure 11 but in terms of changes in mean summertime temperate for an office building and with the inclusion of locations which experience dramatically different weather. We see that although some of these new points lie a little further away from the centre trend, the distance is minor. Hence we can conclude that the concept of a climate change resilience coefficient is valid even for fundamental changes in the weather.

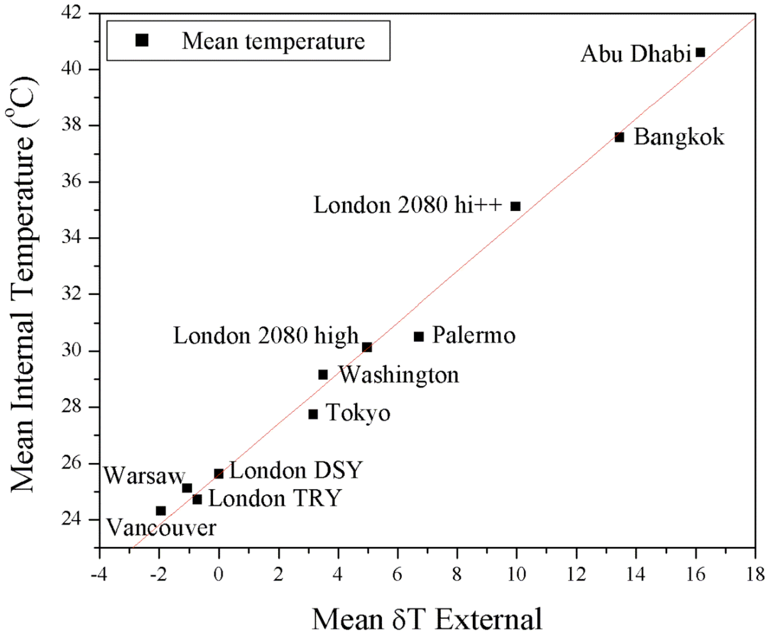

Figure 12. Comparison of the response of a building to various changes to the climate given by morphing the current test reference year and by moving the building to locations where the fundamental weather is very different: the climate change resilience coefficient seems to be itself resilient to any such change.

The Question of Thermal Comfort

We have shown that the response of a building to a changing climate is linear when discussing changes in internal temperature. But what about changes in thermal comfort as a result of climate change? Even if a radical change in climate and weather leads (as Figure 12 shows) to changes inline with UKCIP02-based morphing of the UK's historic weather, is this also true of comfort? Might drastic changes in humidity caused by, for example, placing the building in Bangkok, change the relative response of the building? Figure 12 shows this response in terms of the change in percentage of people dissatisfied (for a single building) as a function of changes in the mean external summertime temperature found from the weather file. We see that the response function of the building is still approximately linear through the central portion of the plot, but the results show a great variance and are obviously constrained by the limits of 0 and 100%. This suggests that away from these limits, mixed resilience coefficients such as:

$$\frac{d\delta PPD_{\text{mean}}}{d\delta T_{\text{mean,external}}} = C_{PPD_{mean}/T_{mean}}$$

may be useful.

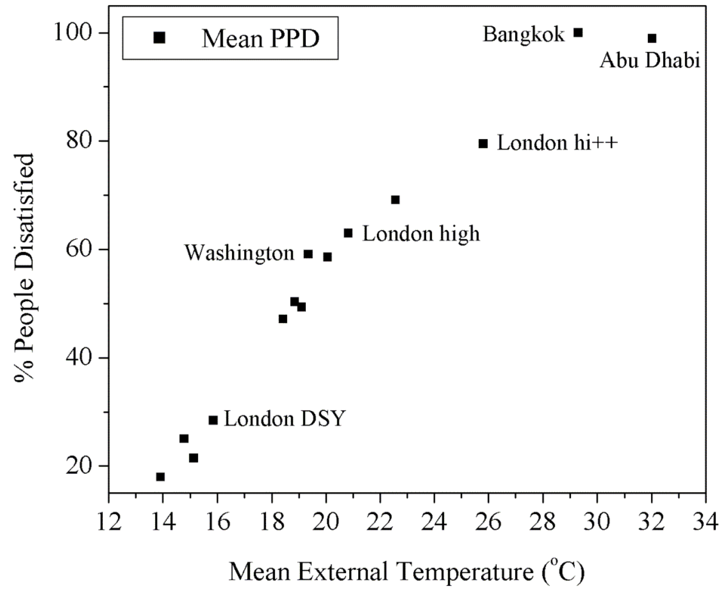

Figure 13. Comparison of the response of an office building (in terms of comfort) to various changes to the climate give by morphing the current test reference year and by moving the building to locations where the fundamental weather is very different: the concept of a climate change resilience coefficient seems to still be valid.

References

VEI99 Veizer, J., Ala, D., Azmy, K., Bruckschen, P., Buhl, D., Bruhn, F., Carden, G.A.F., Diener, A., Ebneth, S., Godderis, Y., Jasper, T., Korte, C., Pawellek, F., Podlaha, O. and Strauss, H. (1999) 87Sr/86Sr, d13C and d18O evolution of Phanerozoic seawater. Chemical Geology **161** 59.

RAH03 Image from http://www.noc.soton.ac.uk/rapid/kt/kt_sov_past.php] data from Rahmstorf, S. 2003, 'Timing of abrupt climate change: A precise clock', Geophysical Research Letters, 30, 10, doi:10.1029/2003GL017115.

UKCIP1 The climate of the United Kingdom and recent trends, UKCIP.

UKCIP02 Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report April 2002.

BEL05 Belcher SE, Hacker JN, Powell DS. "Constructing design weather data for future climates." Building Serv. Eng. Res. and Technol. 2005 **26** 49.