The risk of buildings overheating in a low-carbon climate change future

P.F.G.Banfill[1], D.P.Jenkins[1], S.Patidar[2], M.Gul[1], G.F.Menzies[1], G.J.Gibson[2]

[1] School of the Built Environment, Heriot-Watt University, Edinburgh, EH14 4AS.
[2] School of Maths and Computer Science, Heriot-Watt University, Edinburgh, EH14 4AS.

Email: p.f.g.banfill@hw.ac.uk

Abstract:
An overheating risk tool that is compatible with building performance simulation software has been developed, using principal component analysis to give a statistically rigorous simplification of the UKCP09 probabilistic climate projections. The tool converts a single dynamic simulation output into many hundreds of simulation results at hourly resolution for equally-probable climates from the UKCP09 weather generator. The result is a population of outcomes for the performance of a specific building in a future climate, thus helping the user choose adaptation technologies that might reduce the risk of overheating. The outputs of the LCF tool can be delivered as a risk matrix or a probabilistic overheating curve. The perceptions and requirements of potential users were assessed and, for non-domestic buildings in particular, the need to quantify and assess overheating risk was understood by professionals, with concerns expressed for the ease of incorporation of the UKCP09 projections into this process. The new tool has the potential to meet these concerns.

Keywords:
Buildings, climate change, overheating, thermal comfort.

1. Introduction

The global climate is getting warmer just as buildings have to meet more stringent carbon emissions targets. Because global warming and climate change are widely accepted as being due to increased levels of greenhouse gases in the atmosphere, governments worldwide have pledged to reduce emissions in order to mitigate the future changes, and this has driven the move towards low carbon buildings that are more highly insulated and more airtight, and use less energy, with an increased proportion of that energy obtained from low carbon sources. Unfortunately, there is little sign of occupants operating fewer energy-using appliances (even if these are driven by low carbon electricity) and the incidental gains from such appliances will be retained in the internal environment of such buildings. Together with metabolic gains from occupants, this leads to the potential for serious overheating, as has been observed in schools, offices and dwellings. Overheating may encourage the use of artificial cooling, where none was needed previously, and this introduces a fresh source of emissions, making it more difficult to meet the reduction targets.

At the same time, the buildings that already exist and those being designed must also continue to perform in the environment over their lifetime of several decades. They will have to be able to adapt to future climates, despite having been designed for current climates. The key contextual questions are whether we have an adequate understanding of what the future climate will be and the extent to which this understanding should guide the design and retrofit of the built environment. The objectives of the work described here were, first, to explore how the latest climate projections can be used in the building performance simulations

commonly performed at the design stage in new buildings; second, to understand how building designs can be changed to prevent buildings failing to perform in the future climate; and third, to produce a method that is useful for industry needing to assess overheating.

2. Climate projections

Computer models of the climate have been developed over many years and attempt to replicate the physical processes occurring in the atmosphere (solar radiation, convection etc) and in the oceans (currents, circulation etc) to estimate climate conditions. They are very complicated and intensive in computing power and ultimately predict how the weather variables such as temperature, solar radiation, wind speed and direction, relative humidity, cloud cover will vary with time. Deterministic climate projections, such as those of the UK Climate Impact Programme (Hulme et al, 2002) give a single value of these parameters with no associated indication of uncertainty. These first generation projections are still in use and a so-called morphing algorithm has been used to produce weather data for building design in future climates (Belcher et al, 2005). The latest generation of climate projections – UKCP09 (Murphy et al, 2009) - are probabilistic, giving outputs for different percentiles of probability, or if required the user can obtain all possible iterations of a given scenario (Fig.1). Again, algorithms can be used to interpolate to the required timescale. The UKCP09 projections used in this paper require the user to choose an emission scenario (low, medium, high), the time period of study (2010-2099) and the location (5km grid squares in UK), from which the weather generator outputs hundreds of climate files, each equally probable.
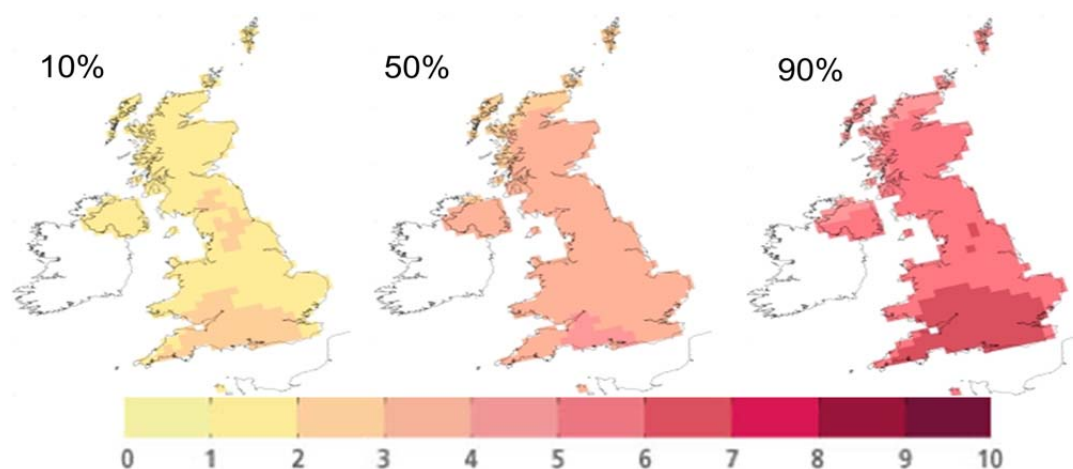

Fig.1: 10, 50 and 90th percentiles of the probability of increase in average temperature (°C) across the UK in the 2080s. The 90th percentile means that there is a 10% probability of the temperature rise being greater than that shown (UKCP09).

3. Building Simulation

Dynamic building simulation is a computationally intensive method of applying physical models for the heat and moisture transfer through the building fabric, solar gain and the effects of occupancy, taking account of interactions and feedback effects, to show how internal conditions in a building vary over time. From information about the external climate, the building construction and services systems used together with the occupancy profile it provides information on the environmental performance of buildings (such as annual energy consumption, running costs, heating / cooling loads, thermal comfort and carbon emissions).

The effect of changes can be investigated and the design optimised. ESP-r, an open source software, was used in this work, but several commercial software packages are available including IES-VE (2012) which was developed from it, and consequently the tool described in this paper would be readily compatible with IES-VE.

4. Development and validation of the LCF tool

4.1. Regression process for weather data

Since dynamic simulation at hourly resolution gives 8760 data points for a single variable (e.g. internal temperature) in one climate over one year, and a large number of climates are needed to establish probabilities, the amount of information rapidly becomes unmanageable and it is impracticable to simulate a building in every possible climate. The solution chosen here is to emulate the simulation process by multiple regression. In summary, 100 climates are chosen at random from the 3000 produced by the UKCP09 weather generator (Jones et al, 2009) for a particular scenario (e.g. high emissions, 2040-2069 time period, chosen location). The weather generator produces an hourly time series for seven weather variables (temperature, precipitation, relative humidity, vapour pressure, sunlight fraction, direct radiation and diffuse radiation). The internal conditions depend on a contribution of each of these variables both at the current time and, through the inertia of the building fabric, a contribution at each of the preceding 72 hours. Therefore there are 504 (=7x72) input weather data points at each hourly value. It is to be expected that there will be correlations between these variables but without making any assumptions about their precise nature, Principal Component Analysis was used to simplify the correlations between pairs of variables (Patidar et al, 2011). PCA is a statistical method for analysis of data with a high number of dimensions, and can transform a large number of variables which are possibly correlated together into a small number of uncorrelated variables. PCA was done in two steps: first, exploiting the correlations within the 72 hours of each individual weather variable, and then exploiting the correlations between different weather variables. This reduced the 504 components to 33 sub-components, made up of 11 for temperature, 6 for precipitation, relative humidity and vapour pressure, and 16 for sunlight fraction, direct radiation and diffuse radiation. The transformed data in the 33-dimension set retained 95% of the total variation in the original dataset (Patidar et al, 2011). Multiple regression was then used to establish a simple linear relationship between the transformed dataset from the randomly selected climate file and the corresponding building simulation outputs. This regression based approach drastically reduced the number of building simulations that must be carried out for a climate scenario, and hence the time taken, and this made emulation feasible.

The multiple regression approach has also proved to be effective for performing a systematic analysis of various aspects of heatwaves, including the frequency of extreme heat events in future climates, their impact on overheating issues and effects of specific measures to offset overheating (Patidar et al, 2012). Indoor temperatures could be correlated with extreme air temperatures in a heatwave, with effects that differ subtly from those obtained by analyzing the effect of an average rise in temperature over a year.

4.2. Application in building simulation

The starting point for the use of the LCF tool is a single dynamic simulation at hourly resolution using ESP-r, IES-VE or similar for a single weather file. This simulation needs to

be done afresh for each building version that is to be investigated and yields a results file, giving internal temperatures, heating or cooling loads, etc also at hourly resolution. This single results file is sufficient to calibrate the coefficients in the multiple regression equation. Having specified some information about the building, such as times of occupancy, the assessment criterion (e.g. 1% of occupied hours above 28°C), the form of assessment required (overheating or load analysis) and the chosen future climate scenarios, the user can then run the tool from the weather file and the results file. The tool incorporates up to 1000 weather files from the UKCP09 weather generator for each climate scenario (emissions level and timeline) to deliver hourly results, such as temperature in each zone of the building (Jenkins et al, 2011). These outputs are automated so the user can choose between several graphical or textual formats. The whole process is complete in about half an hour.

Validation of the tool has been carried out on different versions of four buildings by running 100 hourly dynamic simulations and comparing them to 100 hourly regression model profiles that effectively emulate the simulations. In real use, all 100 hourly dynamic simulations are not needed; only the single calibration simulation is necessary and this saves considerable computing time, making the tool a practicable add-on as part of the building design process. Fig. 2 shows the good agreement (i.e. small residual differences) between the emulated results and the dynamic simulation results for a typical house: more than 93% of the hourly temperatures are within ±1.5°C of the simulation (Jenkins et al, 2011).
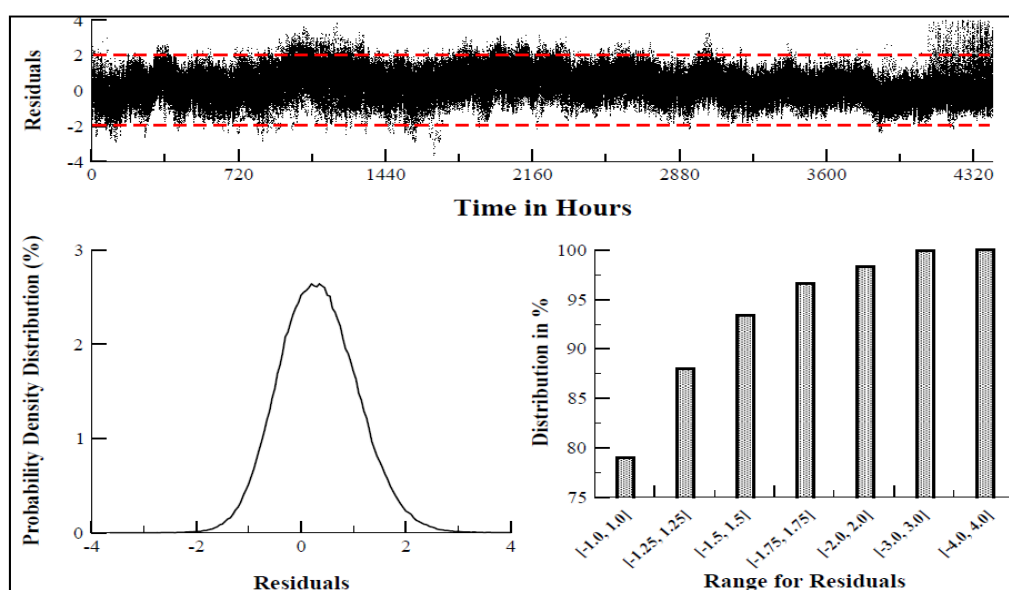

Fig.2: Validation of the regression model for a house in London under the medium emission scenario for the 2020-2049 period, based upon 100 representative weather files. The residuals are the differences between the hourly temperatures estimated by 100 dynamic simulations and by the regression model.

4.3. The LCF tool outputs

As already noted, the tool can provide output in several forms. Fig.3 shows a comparison between a future climate scenario and the baseline performance of the same building in the current climate. It shows the cumulative frequency of the percentage increase of the overheating metric (number of hours over 28°C) compared to the average for the baseline scenario. It indicates that the house has a 96% probability of being warmer if no action is

taken, whereas using a simple window opening adaptation reduces this to 72%, and, combined with external shading and reduced internal heat gains from equipment, the probability is further reduced to 14%. An alternative way of understanding this information is to choose a level of risk that might be acceptable for a designer. For example a 90% probability level would cover all but the most extreme results from the tool. If designing to this level for the same future climate Fig.2 shows, with 90% certainty, that the number of hours above 28°C for this building will show an increase of at least 8% when no adaptation is used but a decrease of at most 10% when the windows are opened and a decrease of at most 42% when windows, shading and reduced gains are all employed. Fig.4 shows that the progressively warming climate increases the probability of overheating in the unadapted house, expressed as the percentage of occupied hours above 28°C. Again 96% of climates in the 2080s medium emissions scenario will give more than 1% of occupied hours above 28°C. A further, simpler display of the overheating risk is shown in Fig.5, where the graphical colour-coding corresponds to the value on the vertical overheating threshold line in Fig.4; the value corresponding to 96% of climates in the unadapted house is indicated by the intense colouration in the chart. This also shows other climate scenarios, processed in the same way as the London, 2040-2069, medium emission scenario of Fig.3.
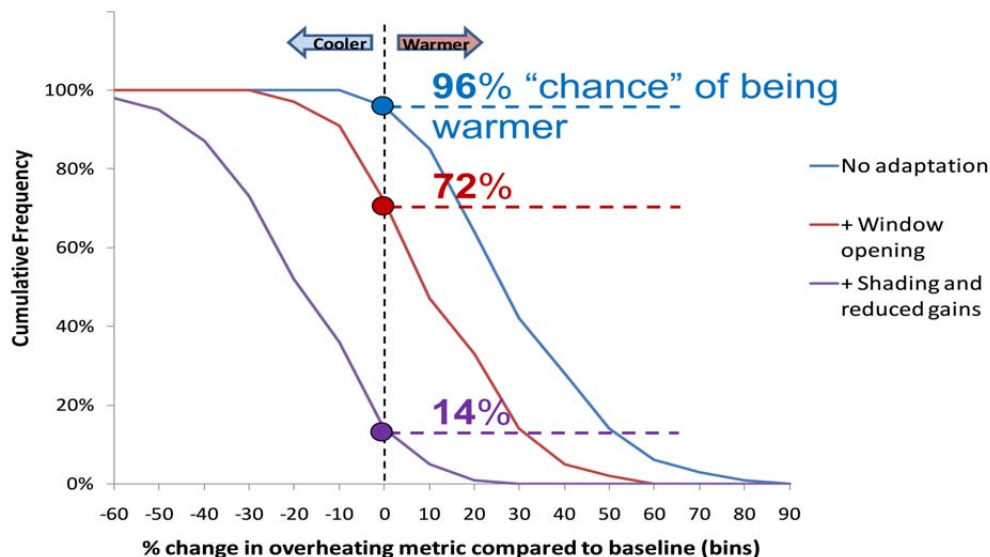

Fig.3: A probabilistic failure curve, showing % change in the number of occupied hours above 28°C for a 3 bedroom detached house in London, 2040-2069 climate, medium emissions.
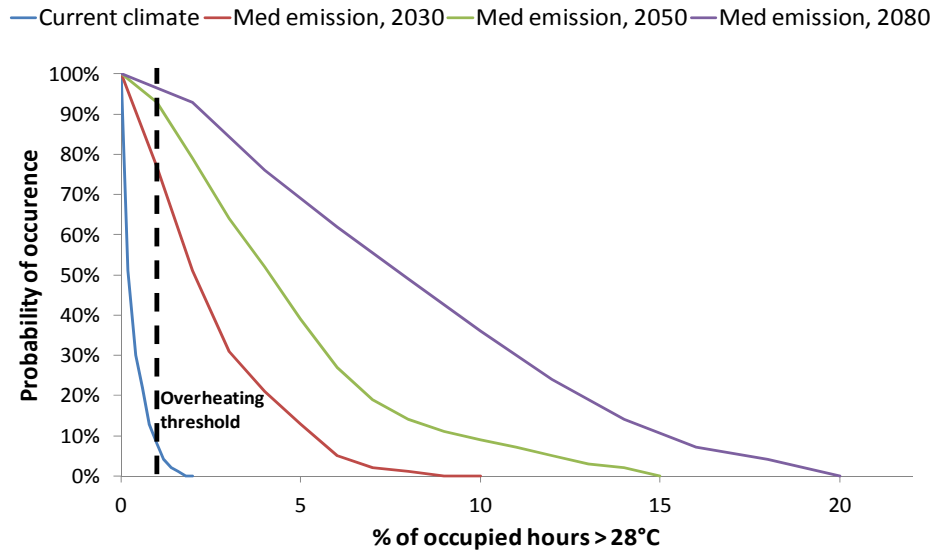
Fig.4: Effect of climate change on the same house as Fig.3 with no adaptation measures used.
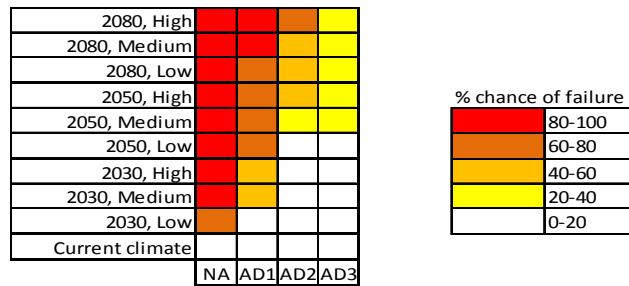

Fig.5: A simplified representation of the data from Figs.3 and 4. NA = no adaptation (baseline), AD1 = window opening, AD2 = AD1 plus shading, AD3 = AD2 plus reduced gains.

5. Relevance to design professionals

A series of focus groups, interviews and questionnaires were administered with professionals working in building design in order to elicit their preferences for the form of a possible design adaptation tool and to translate the outcomes to a practical level. 46 responses to a questionnaire on present building design practice showed that typically buildings are designed to minimize capital cost and to comply with (rather than exceed) current legislation / regulations. Assessment of overheating is not a priority and optimization of performance in a future climate would not normally be considered unless driven by the future occupant (Gul and Menzies, 2012). These themes informed the questions used in focus groups and interviews, in which 41 professionals participated. The research questions addressed whether overheating is seen as a problem, the kinds of climate data, tools and software in current use in building design, use of probabilistic climate projections and the preferred form of an overheating tool (Gul et al, 2012).

Overheating is not currently considered as a risk in the domestic sector but it is seen as increasingly important in non-domestic buildings, with inappropriate fabric, south-facing glazed facades and inadequate ventilation giving concern. However, the typical professional's

response is to put in some cooling provision to deal with overheating. Future overheating is seen as a problem for complex buildings and schools, rather than housing, although it is recognized as becoming an issue in new dwellings in southern UK. In the non-domestic sector, something happening in 50-60 years is not high on the industry's agenda and there is minimal concern for future overheating risks, partly because cooling plant is over-sized and, with a limited lifetime, is likely to be replaced before the problem gets serious. Climate data is scarcely used in domestic building design, which is based on the feeling that "it worked last time", whereas non-domestic designers use detailed data if required, in which case CIBSE Test Reference Years are the benchmark, although designers lacked guidance on which climate files to choose. Probabilistic climate projections are perceived as a valuable way to look ahead and allow adapting to future climates but will only be used if required by law, and even then they must be user friendly otherwise there will be limited uptake. Overheating analysis is considered to be a resource intensive exercise that would not always be justifiable to a client, and as a result the domestic sector relies on basic steady state calculations like SAP or PHPP, whereas in non-domestic buildings SBEM (steady state) would be supported by dynamic simulations using IES-VE, TAS, ESP-r, Hevacomp and ClassCool.

Accepting that an LCF tool will be needed eventually, professional preference is for something that can be added simply to existing modeling procedures, which would need to be cost effective, and preferably sit within a single level of expertise within an organization. As a software solution, it might end up being part of the Building Regulations and therefore use the same building specifications as those required for SAP calculations. One professional suggested that "two levels of a tool, one with a high level of information for someone trying to understand the issues, and another simple one that can be used for a report" would be suitable, but another was cynical about the cumulative probability graph (Fig.3) because it would be off-putting to people who struggled with graphs at school. This suggests that the colour-coded display such as Fig.5 might be more appropriate, although this could be given in addition (rather than as an alternative) to the output shown in Fig.3.

6. Discussion

The LCF tool has proved to be useful and efficient in carrying out the overheating analysis of naturally ventilated buildings, for which it was originally designed. In this situation its delivery of temperature in the different zones of a building at hourly resolution enables it to assess the probability of failure, expressed in terms of the percentage of occupied hours above a threshold temperature. However, it works equally successfully for the analysis of cooling and heating loads in mechanically ventilated buildings, where the failure criterion is more difficult to define. For example, neither cooling nor heating plants are normally sized to close tolerances, so an increase in cooling load is only likely to result in a higher number of hours of operation and a decrease in heating load is likely to result in lower heating plant efficiency. Neither of these are clear cut 'failures' but the LCF tool could be applied to assessment of cooling energy consumption and associated CO_2 emissions.

Further validation on more buildings and using different adaptation technologies will be needed in order to test the limits to application of the tool, and based on feedback from potential users different forms of output can be tailored to be more specific to the needs of particular clients. The format chosen for the improved interface will depend on whether the tool is to be used as an open-source, stand-alone model or within existing building simulation software or used as a consultancy tool by the developers. It is recognized that it would not

immediately be a routine tool for every design, but rather an additional analysis that some clients might value. However, its potential will be realized in the future, when deterministic climate projections are recognised to be no longer adequate. It is difficult to imagine that subsequent generations of climate projections after UKCP09 will revert to deterministic forms, and probabilistic projections will eventually be accepted as normal, whereupon the LCF tool could be adopted as the industry standard.

Since the tool can run multiple weather files for the same building, it is compatible with other climate projections and it could be useful for the study of other climate variations like locations, micro-climates and altitude or coastal factors. The advantage of the tool is that a single building simulation is all that is required in order to carry out sensitivity analysis on these factors.

Finally, as hinted at above, the failure analysis can be converted into an energy analysis in order to answer questions on the most probable energy consumption of a building for a given future climate scenario. This could be done at a single building scale or, suitably scaled up with appropriate diversity, to the district, city or region scale and would therefore be useful for power network operators needing to assess the capacity of infrastructure to meet the demands of buildings.

7. Conclusion

Calculating overheating risks due to probabilistic projections of future climates through empirical regression formulae based on a single simulated climate can achieve very similar results to those of detailed simulations of many different climates. A validated tool that converts the building performance results from a single weather file into multiple climate results has been developed. It gives satisfactory results for different building types, with about 80% of hourly temperatures being within ±1°C of the simulated values, based upon over 20000 annual simulation results. A prototype user interface gives efficient use and delivers outputs that describe the results in terms of probability of failure, either as a risk matrix or a probabilistic overheating tool.

8. Acknowledgements

References:
Belcher, S.E. et al. (2005), *Constructing design weather data for future climates*, Building Services Engineering Research and Technology, **26**, 49-61.
Gul, M. et al (2012), *Tailoring a future overheating risk tool for existing building design practice in domestic and non-domestic sectors*, Building Services Engineering Research and Technology, **33**, 105-117.
Gul, M., Menzies, G.F. (2012), *Designing domestic buildings for future summers: Attitudes and opinions of building professionals*, Energy Policy, **45**, 752-761.
Hulme, M. et al (2002), *Climate change scenarios for the UK: The UKCIP02 Scientific Report*, Tyndall Centre for Climate Change Research, University of East Anglia, UK.

http://www.ukcip.org.uk/wordpress/wp-content/PDFs/UKCIP02_tech.pdf (Accessed 19/7/2012)

IES-VE (2012), *Introducing the virtual environment*, Integrated Environmental Solutions, www.iesve.com/software/ (Accessed 16/7/2012).

Jenkins, D.P. et al (2011), *Probabilistic climate projections with dynamic building simulation: predicting overheating in dwellings*, Energy and Buildings, **43**, 1723-1731.

Jones, P.D. et al (2009), *UK climate projections science report: projections of future daily climate for the UK from weather generator*, http://ukclimateprojections.defra.gov.uk (Accessed 20/7/2012).

Murphy, J. et al (2009), *UK Climate change projections science report: climate change projections*. Technical report, Meteorological Office Hadley Centre, Exeter, UK. http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87893&filetype=pdf (Accessed 19/7/2012).

Patidar, S. et al (2011), *Statistical techniques to emulate dynamic building simulations for overheating analyses in future probabilistic climates*, Journal of Building Performance Simulation, **4**, 271-284.

Patidar, S. et al (2012), *Analysis of probabilistic climate projections: heat wave, overheating and adaptation*, Journal of Building Performance Simulation, **5**, 1-13 (iFirst article).