Editorial article: The Implications of a Changing Climate for Buildings

Pieter de Wilde [(1)] and David Coley [(2)]
(Guest Editors)

(1) School of Architecture, Design and Environment, University of Plymouth, Plymouth, United Kingdom
(2) Department of Architecture and Civil Engineering, University of Bath, Bath, United Kingdom

Abstract: With a growing global concern about climate change, the building industry is facing the question of how predicted changes in climate will impact on the performance of buildings around the world. This is resulting in a fast-growing field of research that focuses on the adaptation and resilience of buildings to a changing climate. This review paper sets the scene for a special issue of *Building and Environment* on this subject. It discusses the relationship between climate change and buildings and the emerging body of knowledge on the subject, as well as classifying and summarizing the contributions to this special issue.

Keywords: climate change, environmental effects, impact on buildings and occupants

1 Introduction

This special issue of *Building and Environment* deals with the implications of a changing climate for buildings. Climate change is considered to be one of the main challenges facing humankind in the 21th century, with serious and global consequences for the environment [1], human health [1, 2], and the economy [3]. In itself, the built environment is a significant contributor to greenhouse gas emissions. For typical developed nations like the OECD countries, about 24 to 40% of anthropogenic greenhouse emissions will be related to buildings; 40 to 95% of these emissions will be caused by operational energy use with the remainder being caused by construction and demolition [4, 5]. At the same time, the performance of buildings depends on the climate they are exposed to. Their long lifetime (in the range of 50 to 100 plus years) corresponds to the timescale over which the climate is expected to show substantial change. This implies that buildings built today need to be designed to work successfully in both the current and future climate, and with the aim of reducing the greenhouse emission burden they place on this and future generations. While greenhouse gas emissions and climate change are thus intrinsically linked, traditionally most attention is paid to curbing emissions and climate change mitigation. The special issue focuses on the reverse relation: adaptation or resilience of buildings towards climate change.

This review paper sets the scene for the special issue, starting off by providing an overall introduction to the interaction between buildings and climate change. It then describes the emerging body of knowledge in this specific field, giving an overview of the key publications of the last decade. It summarizes the contributions to the special issues and classifies them, demonstrating the main current research themes in the field, and discussing the geographical coverage. The paper concludes by combining the main findings from the contributions to the special issue, in an attempt to identify needs for further research and limitations of the current state-of-the art.

2 Climate change and buildings

Buildings provide an interface between the outdoor environment, which is subject to climate change, and the indoor environment, which needs to be maintained within a range that keeps the building occupants safe and comfortable, and which is suitable for any key processes that are taking place within the building. Figure 1 conveys the complexity of this relationship. The columns in Figure 1 contain, from left to right: (a) climate change as a driving force; (b) the environmental effects of climate change that pertain to buildings; (c) the likely impact of those environmental effects on specific buildings; and (d) potential consequences for building occupants and key processes taking place in buildings. The figure is simplified and for instance does not show the feedback loop where an increase in building emissions contributes to further anthropogenic climate change.

[Insert figure 1 here]

Figure 1. Schematic overview of the main mechanisms in which climate change impacts on buildings, building occupants, and the key processes taking place in buildings. Figure based on a graph by McMichael et al (2006) [2], depicting the relation between climate change and health effects, but expanded to include the building as interface, as well as comfort and key processes taking place in buildings.

Climate change is a field of study in itself, carried out by climate and earth scientists and other specialists. It is concerned with keeping the climate record, explaining any changes to that record, as well as with predicting future changes. The seminal work in this area is the IPCC report 'Climate Change: the Physical Science Basis' [6]. The field is not without controversy, and major gaps in our understanding of climate change remain [7]. However, most of the debate focuses on what fraction of climate change is caused by anthropogenic emissions and what fraction by natural drivers [8, 9], how great the changes will be, and what actions are needed to stop or even reverse these changes [10, 11]. Almost all climate modelling ignores various difficult to predict feedback processes, for example, increases in methane emissions from melting permafrost. Should these prove important, climate change could occur much more abruptly than normally assumed [12].

Most climatic models point to a substantial future change in climate of approximately plus1.5^{o}C in annual mean temperature by 2050 and 2-4^{o}C by 2080 when averaged over the planet's surface and under the conservative assumption that the atmospheric concentration of carbon dioxide (the main anthropogenic greenhouse gas) will have only increased to 600 ppm [6]. As less change is predicted over the oceans, because of their greater heat capacity and their ability to loose heat via evaporation [13], a greater change is expected over land.
The models also indicate that even over land the change will not be even, with areas such as Alaska and Canada experiencing a warming of 10^{o}C change due to a reduced period of snow cover [6]. To put these numbers into perspective, the annual mean temperature difference between the northern Mediterranean coast around Nice and London is only 5^{o}C [14]. It is therefore clear that the effect is not a minor one and that the implications for the built environment are likely to be large.

As discussed, climate change drives changes at a regional or local level. In Figure 1 these are presented as environmental effects. From a building point of view, these effects range from slight gradual changes (for example a slight rise in average ambient temperature) to extreme events (for example flooding). This local viewpoint strengthens the need to change the focus from a generic climate to specific local weather conditions. Additionally, climate change might impact the context in which buildings are positioned. For instance, in terms of ecosystems this might have implications for specific animal or plant species, and thus for land use (for example farming or the spread of disease) and the urban fabric (for example consequences leading to economic and societal change). While global forecasts might be reasonably accurate, predicting local environmental effects is more difficult: the higher resolution that is needed to create regional and local predictions is bought at the price of higher uncertainties [7].

These changing environmental effects then have an impact on building behaviour and performance. Typical areas affected are energy use and emissions, inefficiency and malfunction caused by systems confronted with a shift in operation conditions, and problems caused by overloading. Furthermore the environmental effects might cause issues in the urban context, like failures in the electrical grid, which can cause problems for buildings that in themselves are functioning properly. Many of these impacts need to be discussed in terms of risk, with recent work on flood insurance in the Netherlands providing a good example [15].

The impact of climate change on buildings is deeply intertwined with consequences for the building occupants and key processes that take place in those buildings. As buildings have different functions, climate change impact assessment studies must be tailored towards the specific needs and requirements at hand. Complex interactions exist: for instance between the comfort as experienced by occupants, control settings in the building, and energy consumption of heating and cooling systems [16]. Note that many buildings are designed to only just meet national guidance on overheating and large change in external temperature is more than likely to take such building into problematic conditions, particularly as the bulk of the increase in mean annual temperature is expected to be during the summer months. Assuming the overheating criteria were set in a sensible manner, and given the lifetime of a building is such that the predictions are that it will experience substantial climate change, one can conclude that modelling for design and compliance should be completed using both current and future climates.

The implications of climate change for the complex interaction between buildings, occupants and key processes in buildings form the focus of this special issue.

3 The emerging body of knowledge

Climate impact assessment studies require a definition of the future conditions that will be considered in the analysis (i.e. the climate change scenario and the control settings), a definition of the object under investigation (a building and its (sub)systems), and a focus for observation and quantification (definition of appropriate performance metrics).

Climate data for building performance studies

Predicting future climatic conditions is the starting point to all climate change impact studies. Driven by the fact that most building related studies are undertaken by means of transient building simulation tools that require an hourly dataset to represent a year of climate data, one area that receives a lot of attention is the conversion of more generic climate change predictions to hourly datasets. Guan, in a recent review of this area, [17] discerns two approaches to obtaining hourly datasets: predictions based on historical data, and predictions based on fundamental physical models. She sub-divides the first category (historical models) in *extrapolation of previous datasets* and *imposed offset methods*, where a historical pattern is mapped to an average change. There also is a third alternative for historical datasets: the substitution of measured data from other geographical locations to mimic changed conditions [18]. Guan subdivides the second category (physical models) in *stochastic models* and *global climate models*. These global models are seen in a lot of the literature on climate change under the name of General Circulation Models (GCM). Regional models then can be attached to these General Circulation models; one well-known example is the UK MetOffice's HadRM3 model that in turn produces regional (25 km resolution) projections of the future climate. Resulting datasets for the UK are the UKCIP02 and the UKCP09 datasets, with the latter taking a much broader, probabilistic approach. Work is starting to appear which looks in-depth at specific aspects of the climate change predictions, such as solar irradiations in these datasets; see for instance Tham et al [19]. Efforts to generate various types of climate files that can directly be used with building performance simulation tools are the Prometheus project [20] and the design refence years by Du et al [21]; Mylona [22] provides an overview on the recent CIBSE work in this area. Nik et al [23] demonstrate the use of regional climate models in the Swedish context. For most building simulations reported in the literature, use has been made of imposed offset methods. The prevailing approach has been developed by Belcher et al [24] and is generally known as 'morphing'. Crawley has applied this method to create climate files to represent the future climate of no less than 25 locations all over the world, covering 20 different climate regions [25]. Chan [26] reports on application of morphing for Hong Kong's subtropical climate. However, morphing is not without criticism. De Dear questions the use of current climate variation onto future decadal changes, and wonders whether global circulation models with a high spatial resolution would not be just as suitable to provide a high temporal resolution [27]. Guan [17] notes the lack of cross correlation between separate weather parameters in the morphing method, and introduces a mixed approach to address this issue. Eames et al [28] discuss the spatial resolution of climate change prediction and clearly demonstrate a need to take into account the local geographic conditions. Recent work in the field is now demonstrating a direct application of (probabilistic) climate prediction data in building simulation; see for instance Kershaw et al [29], Tian and de Wilde [30] and Jenkins et al [31]. Note that an additional impact on climate conditions in cities, amplifying warming conditions, can be expected from the urban heat island (UHI) effect [32, 33, 34].

Climate change impact studies for the built environment

The most frequently quoted report in this area is probably 'Climate change and the indoor environment: impacts and adaptation' [35]. While limited to the UK, it covers a broad range of building types: a 19th century house, a new-build house, a 1960s flat, a new-build flat, a naturally ventilated 1960s office, a modern mixed-mode office, a mechanically ventilated high thermal mass office, an advanced naturally ventilated office, a fully air conditioned office, a 1960s school, and an advanced naturally ventilated school. Additionally the work also looks at possible interventions to adapt buildings to climate change. Summaries covering sub-sections of this report have also appeared as separate journal papers [24, 36].

Studies covering single building types for specific locations are proliferating. While a full overview of all work in this area is beyond the scope of this review article, the following gives a flavour of some of the work that has been published in the main building science journals. For residential buildings, Gaterell and McEvoy [18] present a climate change impact study for existing detached properties in the UK, while Hacker et al [37] cover semi-detached homes. Collins et al [38] also study UK domestic buildings, with a focus on the impact of increased use of cooling. Frank [39] have analysed the potential impact on generic residential buildings in Switzerland. Wang et al [40] focus on a residential base case building and various more energy efficient variants in Australia, while Chan [26] presents the case for Hong Kong. In the office sector, Radhi [41] has conducted a climate change impact study for air-conditioned buildings in the United Arab Emirates, while Wan et al [42] cover air-conditioned offices in China; Chan [26] gives the Hong Kong situation. Chow and Levermore [43] have analysed the impact on office buildings in the UK, looking at various existing types of facades and potential upgrades. Frank [39] has also analysed the potential impact of climate change on office buildings in Switzerland. Crawley [25] studies the impact of climate change on a small office building, with 'low energy' and 'developing country' variants, at the 25 locations all over the world covered by his climate data work. Ouedraogo et al [44], in one of the few publications that deals with an African nation, have studied the impact of climate change on typicall public and commercial (office) buildings in Burkina Faso. There are less publications covering other building types. Within the UK's TARBASE project, Jenkins et al [45] have focussed on the overheating risk of future low carbon schools; while Taylor et al [46] have studied the emissions of UK hotels. Jentsch et al [47] study a University building. Du et al [21] cover a wide base of building types, including an airport, accomodation for elderly, hotel, museum, school, prison, archive, theatre, library, hospital as well as homes and offices in the context of developing and testing a future design reference year. However, all these other categories seem to warrant further investigation. The overall conclusions of these studies are well articulated by Crawley [25] who states that the impact of climate change will result in a reduction in building energy use of about 10% for buildings in cold climates, an increase of energy use of up to 20% for buildings in the tropics, and a shift from heating energy to cooling energy for buildings in temperate climates. More recently, further work has started to appear that deals with the impact of climate change of specific building systems, especially ventilation. In this category, Lomas and Ji [48] have studied resilience of naturally ventilated buildings in the UK; Barclay et al [49] have carried out similar work but emphasize the issues associated with wind predictions in using UKCP09 data. Delfani et al [50] looked at the impact of climate change on evaporative cooling systems in Iran. Kendrick et al [51] have investigated the impact of thermal mass; Porritt et al [52] have investigated the interventions in dwellings that would reduce overheating during future heat waves. Smith et al [53] have studied the impact of climate change on the prospects of evaporative cooliing systems. Some research on specific building types and systems is still inconclusive; for instance there are conflicting reports on the impact of climate change on the more energy efficient building variants: Crawley [25] reports that these are less sensitive to change, whereas Wang et al [40] come to the opposite conclusion. At another scale, climate change impact studies are also applied to an urban level. Zhao et al [54] discuss the factors that play a role in the urban heat island effect in in Beijing, China, pointing at the Chinese urban planning tradition that dates back 3500 years. Emmanuel and Krüger [55] have studied the UHI developments for Glasgow, UK, and attempt to establish resilience towards future trends. Mourshed [56] reports on the probable consequences for Dhaka, Bangladesh. Finally, novel work outside the realm of thermal behaviour that deals with the impact of climate change on the performance of drainage systems in properties has been reported by Jack and Kelly [57], with Pyke et al [58] covering stormwater management in the built environment in broader sense.

Performance metrics for climate change impact studies

The overwhelming majority of studies on the impact of climate change on buildings thus far look at relatively straightforward performance indicators: energy use for heating, energy use for cooling, and building overheating. Both energy uses are often combined into one figure for overall energy use, or annual carbon emissions. However, some work is emerging that suggests a need to study alternative or more refined metrics. Lomas and Ji [48] link resilience of passively cooled buildings to their life-expectancy, which can be considered to be a large-scale holistic building performance indicator. McGilligan et al [59] have developed adaptive comfort degree-days to better assess energy consumption under changing climate conditions. At the other end of the spectrum, de Wilde et al [60, 61] suggest looking more closely at zonal and temporal resolution of performance indicators, as climate change effects for specific areas in a building might be masked by an overall metric and gradually change over time. They also identify a need to link thermal performance to other aspects like predicted performance for office work [60], similar to links with health effects as described by McMichael et al [2]. Almas et al [62] combine regional climate models with building stock models to quantify the risk of wood decay in timber structures, bypassing the study of single buildings.

An additional avenue of research is the study of the balance between embodied CO_2 and operational CO_2 emissions; initial work in this direction is presented by Hacker et al [37], with more recent work reported by Williams et al [63]. Other recognized areas of interest associated with the impact of climate change on building performance are risk-based categories like vulnerability, damage potential and reversibility [64]; performance indicators in these areas largely still remain to be developed.

Further work

Many authors mention the inherent uncertainties in climate change impact studies. For instance Lisø reminds us that ‘ *there are large uncertainties associated with the future performance of buildings due to changes in regional- and local-scale climatic impact*’ [64]. Guan [17] points out that ‘*unlike most other scientific work, projections of climate change cannot be validated, since they do not relate to a currently replicable event*’. Jentsch et al [47] show that as a consequence predictions might look flawed or meaningless, for instance in a case where results for the past summer of 2006 show a worse performance than the predicted hot summer of 2050. Yet surprisingly few researchers are taking this issue into account and developing a probabilistic approach [65]. Some initial work in this area is described by de Wilde and Tian [60, 66, 67].

As is the case in much building simulation work, dealing with the human factor remains an issue needing further attention. De Dear [27] points out the need to look more closely at the modelling of the interaction of building occupants with building systems, as this interaction is likely to change with the climate conditions.

On a more generic level, Morton et al [68] have looked at the beliefs about climate change in a large international engineering firm and studied how this might impact any actions taken within the building industry.

4 Content of the special issue

The special issue starts with a series of climate change impact assessment studies that cover individual buildings, building systems as well as the urban realm.

For individual buildings, Guan has conducted climate change impact studies for air-conditioned offices in Australia. Using sensitivity analysis, she concludes that a key area for adaptation to climate change is reduction of the internal heat load, with lighting load and plug load being particular targets. Gupta and Gregg present a climate change impact study for English homes, studying the risks posed by climate change as a combination of hazard, vulnerability and exposure. Amongst various adaptation measures they find user-controlled shading to be the most efficient alternative approach. However, they also find that overheating risk cannot be completely eliminated. Huijbregts et al present climate change impact studies for museums, analysing the risk of climate change to museum collections housed in historic buildings. They highlight the importance of increased relative humidity, which raises the prospects of mould growth and mechanical damage to objects. Lomas and Giridharan focus on the potential impact of climate change on the internal temperatures in hospital wards, which is crucial since these are occupied by vulnerable people. They present a methodology to assess thermal comfort in depth under both present and future climate conditions. A case study, Addenbrooke hospital, shows the alignment of monitoring, modelling and calibration, and the use of simulation with climate projections to ensure that these hospital wards are resilient to climate change. The companion paper to Lomas and Giridharan by Short et al continues on the subject of resilience of hospitals towards climate change, using the same case study (Addenbrooke hospital), but takes a more holistic environmental performance view, moving beyond thermal comfort only. The paper analyses various refurbishment strategies that have can be applied to maintain performance, positioning them in a line of previous interventions. . The authors conclude that full air conditioning is not necessary, and undesirable from an energy efficiency point of view. Nik et al have developed a hygro-thermal model to analyse mould growth risk as a consequence of climate change for attics in Swedish homes. Their work predicts that current mould growth problems will only increase with further climate change. Various options are presented to reduce this mould growth risk, with mechanical ventilation being the safest solution.

At the building system level, Hanby and Smith use a probabilistic approach to study the potential of evaporative cooling systems to cool a single zone office building under future climate conditions. They conclude that present plant configuration and capacity are viable into the 2050s, but also note that it is likely that by then systems will have been updated or replaced with more efficient technology.

At the urban level, Mavrogianni et al investigate a broad range of domestic buildings that represent the housing stock in London. The work establishes a correlation between building geometry, building age and overheating risk. It also highlights the role of insulation levels as well as the position of this insulation in overheating, and points out the need to take this into account when upgrading dwellings to reduce heating energy use. Williams et al study the risk posed by climate change to UK suburbs with a focus on increased temperatures and heat waves, changes in precipitation and extreme weather events, and also consider adaptation and mitigation options. Apart from the typical focus on technical aspects they also consider the societal aspects, which is particularly important where the object of investigation is homes.

Other work addresses the impact of climate change on building design and policy. Pyke et al approach climate change from the perspective of the voluntary LEED green building certification system. They present a *climate sensitivity index* and a *climate adaptation opportunity index* that add climate change impact credits to the LEED rating. They apply these indices to a set of certified projects, with yields interesting results in terms of regional sensitivity and opportunities within the US building stock. Robert and Kummert conduct a climate change impact study for a net-zero energy building, demonstrating that changing climate conditions can cause designs in this category to miss their high-profile target.

Finally, the special issue contains work that aims to fill in some of the fundamental blanks in our knowledge base on the implications of climate change for buildings. Coley et al study the prospects of structural and behavioural adaptations to help a school and domestic property cope with climate change. They conclude that for the UKCP09 climate projections behavioural adaptations are capable of compensating for errors in the climate change prediction; however they stress that both approaches must be taken into account when designing buildings that need to be resilient towards climate change. De Wilde and Tian also investigate the role of uncertainties in climate risk impact assessments, but with a view towards facilities management. They find that maintenance, system degradation, system upgrades and renovation are key issues that limit the present predictive capabilities and need deeper investigation. They also find that more advanced performance indicators, such as 'time to intervention', might be more appropriate for climate change impact studies than simple indicators as annual energy use and overheating hours. Steenbergen et al break new ground by investigating the relationship between climate change and the design wind speed used for structural building engineering calculations, noting that future trends in wind speeds have not yet been including in the building regulations. Their approach to deal with extreme events is transferable to other building science domains such as overheating studies.

The contributions in this special issue demonstrate a global interest in the impact of projected climate change on buildings, with contributions from Northern Europe, North America, and Australia. It is notable that many contributions stem from the UK. Apart from a potential bias by the fact that this special issue was initiated from within the UK, there might be other factors that contribute to this effect. One is the prominent role of the UK scientists in climate change projections themselves, which could drive an enhanced interest of policy makers and the general society in related research. This in turn could be leading to more interest in climate change related research in the UK's building science community. Another factor is that climate change is likely to be felt to be of importance in countries that might experience a shift from predominantly heating to predominantly cooling of their buildings. Unfortunately the majority of the work thus far, whether in literature in general or in this special issue, has centred on locations and societies that are expected to be—through either pre-existing climate or wealth—the best able to cope with climate change. Areas like Africa, which is predicted to experience a rise in mean average temperatures roughly 1.5 times the global mean response and which have large populations living in naturally ventilated, low mass buildings, are particularly unrepresented.

Common findings across the various papers in this special issue are:

- A warning that many existent rules and regulations are based on historical climate data;
- The conclusion that existing performance metrics need to be handled carefully, taking into account adaptations in human perception of thermal comfort/discomfort;
- A general statement of the need to conduct more climate change impact studies, to cover (A) a wider range of building types, configurations and systems and (B) further climate scenarios for additional locations.
- The observation that building maintenance, renovation and repair play an important role in ensuring building performance in the long term, and thus have a significant impact on adaptation of buildings to climate change.

In terms of knowledge gaps, we are warned that it is important to balance the efforts invested in climate change impact studies (and increasingly detailed and sophisticated approaches) with actual benefits to practice. Additionally, researchers in building science need to remain critical regarding the climate projections provided by climate change experts; for instance we might need to question the climate change scenarios that represent extreme events with larger return periods.

Finally, the papers in this special issue also provide a series of pointers to further research that is needed to move the area forward:

- Further work on understanding and managing the Urban Heat Island effect;
- A need to investigate the potential as well as implications of occupant behaviour;
- Exploration of the concepts of flexible, robust and resilient building design, integrating concepts for a long lifetime with concepts that allow for adaptation;
- Further R&D on systems that are used within buildings, like HVAC systems, lighting and ICT equipment;
- Development of approaches to rank various mitigation and adaptation strategies.

Acknowledgements

The authors would like to thank Tristan Kershaw, Wei Tian and Rohinton Emmanuel for the help with reviewing abstracts for the special issue.

References

[1] Parry ML. Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change: Cambridge Univ Pr; 2007.
[2] McMichael AJ, Woodruff RE, Hales S. Climate change and human health: present and future risks. The Lancet. 2006;367:859-69.
[3] Stern NH, Treasury GB. The economics of climate change: the Stern review: Cambridge Univ Pr; 2007.
[4] Dimoudi A, Tompa C. Energy and environmental indicators related to construction of office buildings. Resources, Conservation and Recycling. 2008;53:86–95
[5] Gustavsson L, Joelsson A, Sathre R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy and Buildings. 2010;42:230–242
[6] Solomon S. Climate change 2007: the physical science basis: Cambridge University Press; 2007.
[7] Schiermeier Q. The real holes in climate science. Nature. 2010;463:284-7.
[8] Mastrandrea MD, Schneider SH. Probabilistic Integrated Assessment of "Dangerous" Climate Change. Science. 2004;304:571-5.
[9] Lee TCK, Zwiers FW, Xuebin Z, Tsao M. Evidence of Decadal Climate Prediction Skill Resulting from Changes in Anthropogenic Forcing. Journal of Climate: American Meteorological Society; 2006. p. 5305-18.
[10] Hasselmann K, Latif M, Hooss G, Azar C, Edenhofer O, Jaeger CC, et al. The Challenge of Long-Term Climate Change. Science. 2003;302:1923-5.
[11] Karl TR, Trenberth KE. Modern Global Climate Change. Science. 2003;302:1719-23.
[12] Alley RB, Marotzke J, Nordhaus WD, Overpeck JT, Peteet DM, Pielke RA, et al. Abrupt Climate Change. Science. 2003;299:2005-10.
[13] Rowan T, Sutton, Buwen D, Gregory JM. Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. Geophysical Research Letters 2007; 34 (2): L02701.

[14] Coley DA. Energy and climate change. Wiley-Blackwell; 2008 p 331
[15] Aerts JCJH, Botzen WJW. Climate change impacts on pricing long-term flood insurance: a comprehensive study for the Netherlands. Global Environmental Change. 2011;21:1045-1060.
[16] Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings. 2002;34:563-72.
[17] Guan L. Preparation of future weather data to study the impact of climate change on buildings. Building and Environment. 2009;44:793-800.
[18] Gaterell MR, McEvoy ME. The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. Energy and Buildings. 2005;37:982-95.
[19] Tham Y, Muneer T, Levermore GJ, Chow D. An examination of UKCIP02 and UKCP09 solar radiation data sets for the UK climate related to their use in building design. Building Services Engineering Research & Technology: Sage Publications, Ltd. 2011;32:207-228.
[20] University of Exeter, Centre for Energy and the Environment. Prometheus Project Homepage. Available from www.ex.ac.uk/cee/prometheus . Last accessed 6 March 2012.
[21] Du H, Underwood CP, Edge JS. Generating design reference years from the UKCP09 projections and their application to future air-conditioning loads. Building Services Engineering Research & Technology: Sage Publications, Ltd. 2012;33:63-79
[22] Mylona A. The use of UKCP09 to produce weather files for building simulation. Building Services Engineering Research & Technology: Sage Publications, Ltd. 2012;33:51-
[23] Nik V, Sasic Kalagasidis A, Kjellström E. Statistical methods for assessing and analysing the building performance in respect to the future climate. Building and Environment. 2012;53:107-118.
[24] Belcher SE, Hacker JN, Powell DS. Constructing design weather data for future climates. Building Services Engineering Research & Technology: Sage Publications, Ltd.; 2005. p. 49-61.
[25] Crawley DB. Estimating the impacts of climate change and urbanization on building performance. Journal of Building Performance Simulation. 2008;1:91 - 115.
[26] Chan ALS. Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong. Energy and Buildings. 2011;43:2860-2868.
[27] de Dear R. Adapting buildings to a changing climate: but what about the occupants? Building Research & Information. 2006;34:78-81.
[28] Eames M, Kershaw T, Coley D. The appropriate spatial resolution of future weather files for building simulation, Journal of Building Performance Simulation. 2011. p. 1-12.
[29] Kershaw T, Eames M, Coley D. Assessing the risk of climate change for buildings: A comparison between multi-year and probabilistic reference year simulations. Building and Environment. 2011;46:1303-1308.
[30] Tian W, de Wilde P. Thermal building simulation using the UKCP09 probabilistic climate projections. Journal of Building Performance Simulation. 2011; 4:105-124
[31] Jenkins DP, Patidar S, Banfill PFG and Gibson GJ. Probabilistic climate projections with dynamic building simulation: predicting overheating in dwellings. Energy and Buildings. 2011;43:1723-1731.
[32] Mavrogianni A, Davies M, Batty M, Belcher SE, Bohnenstengel SI, Carruthers D, et al. The comfort, energy and health implications of London's urban heat island. Building Services Engineering Research & Technology: Sage Publications, Ltd. p. 35-52.

[33] Kolokotroni M, Ren X, Davies M, Mavroganni A. London's urban heat island: impact on current and future energy consumption in office buildings. Energy and Buildings. 2012;47:302-311.
[34] Tomlinson CJ, Chapman L, Thornes JE, Baker CJ. Including the urban heat island in spatial heat risk assessment strategies: a case study for Birmingham, UK. International Journal of Health Geographics. 2011;10:42
[35] Hacker JN, Holmes, M, Belcher, S and Davies, G. Climate change and the indoor environment: impacts and adaptation. The Charted Institution of Building Services Engineers, London. 2005.
[36] Holmes MJ, Hacker JN. Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. Energy and Buildings. 2007;39:802-14.
[37] Hacker JN, De Saulles TP, Minson AJ, Holmes MJ. Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. Energy and Buildings. 2008;40:375-84.
[38] Collins L, Natarajan S, Levermore G. Climate change and future energy consumption in UK housing stock. Building Services Engineering Research & Technology: Sage Publications, Ltd. 2010;31:75-90.
[39] Frank T. Climate change impacts on building heating and cooling energy demand in Switzerland. Energy and Buildings. 2005;37:1175-85.
[40] Wang X, Chen D, Ren Z. Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. Building and Environment.45:1663-82.
[41] Radhi H. Evaluating the potential impact of global warming on the UAE residential buildings - A contribution to reduce the CO2 emissions. Building and Environment. 2009;44:2451-62.
[42] Wan KKW, Li DHW, Liu D, Lam JC. Future trends of building heating and cooling loads and energy consumption in different climates. Building and Environment.46:223-34.
[43] Chow DHC, Levermore GJ. The effects of future climate change on heating and cooling demands in office buildings in the UK. Building Services Engineering Research & Technology: Sage Publications, Ltd. p. 307-23.
[44] Ouedraogo BI, Levermore GJ, Parkinson JB. Future energy demand for buildings in the context of climate change for Burkina Faso. Building and Environment. 2012;49:270-282.
[45] Jenkins DP, Peacock AD, Banfill PFG. Will future low-carbon schools in the UK have an overheating problem? Building and Environment. 2009;44:490-501.
[46] Taylor S, Peacock A, Banfill P, Shao L. Reduction of greenhouse gas emissions from UK hotels in 2030. Building and Environment.45:1389-400.
[47] Jentsch MF, Bahaj AS, James PAB. Climate change future proofing of buildings--Generation and assessment of building simulation weather files. Energy and Buildings. 2008;40:2148-68.
[48] Lomas KJ, Ji Y. Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. Energy and Buildings. 2009;41:629-53.
[49] Barclay M, Sharples S, Kang J, Watkins R. The natural ventilation performance of buildings under alternative future weather projections. Building Services Engineering Research & Technology: Sage Publications, Ltd. 2012;33:35-50.
[50] Delfani S, Karami M, Pasdarshahri H. The effects of climate change on energy consumption of cooling systems in Tehran. Energy and Buildings. 2010;42:1952-7.
[51] Kendrick C, Ogden R, Wang X, Baiche B. Thermal mass in new build UK housing: a comparison of structural systems in a future weather scenario. Energy and Buildings. 2011;48:40-49.

[52] Porritt SM, Cropper PC, Shoa L, Goodier CI. Ranking of interventions to reduce dwelling overheating during heat waves. Energy and Buildings. 2012. (in press). doi:10.1016/j.enbuild.2012.01.043
[53] Smith ST, Hanby VI, Harpham C. A probabilistic analysis of the future potential of evaporative cooling systems in a temperate climate. Energy and Buildings. 2011;43:507-516.
[54] Zhao C, Fu G, Liu X, Fu F. Urban planning indicators, morphology and climate indicators: a case study for a north-south transect of Beijing, China. Building and Environment. 2011;46:1174-1183.
[55] Emmanuel R, Krüger E. Urban heat island and its impact on the climate change resilience in a shrinking city: the case of Glasgow, UK. Building and Environment. 2012;53:137-149.
[56] Moushed M. The impact of the projected changes in temperature on heating and cooling requirements in Dhaka, Bangladesh. Applied Energy. 2011;88:3737-3746.
[57] Jack LB, Kelly DA. Property-based rainwater drainage design and the impacts of climate change. Building Services Engineering Research & Technology: Sage Publications, Ltd. 2012;33:19-33
[58] Pyke C, Warren MP, Johnson T, LaGro J, Scharfenberg J, Groth P, Freed R, Schroeer W, Main E. Assessment of low impact development for managing stormwater with changing precipitation due to climate change. Landscape and Urban Planning. 2011;103:166-173.
[59] McGilligan C, Natarajan S, Nikolopoulou M. Adaptive comfort degree-days: a metric t compare adaptive comfort standards and estimate changes in energy consumption for future UK climates. Energy and Buildings. 2011;43:2767-2778.
[60] de Wilde P, Tian W. Predicting the performance of an office under climate change: A study of metrics, sensitivity and zonal resolution. Energy and Buildings. 2010; 42:1674-84.
[61] de Wilde P, Tian W, Augenbroe G. Longitudinal prediction of the operational energy use of buildings. Building and Environment. 2011;46:1670-1680.
[62] Almas AJ, Lisø KR, Hygen HO, Øyen CF, Thue JV. An approach to impact assessment of buildings in a changing climate. Building Research & Information. 2011;39:227-238.
[63] Williams D, Elghali L, Wheeler R, France C. Climate change influence on building lifecycle greenhouse gas emissions: case study of UK mixed-use development. Energy and Buildings. 2011;48:112-126.
[64] Lisø¸ KR. Integrated approach to risk management of future climate change impacts. Building Research & Information: Routledge; 2006. p. 1-10.
[65] de Wilde P, Tian W. Towards probabilistic performance indicators for climate change impact studies. Energy and Buildings. 2001;43:3013-3018.
[66] de Wilde P, Tian W. Identification of key factors for uncertainty in the prediction of the thermal performance of an office building under climate change. Building Simulation. 2009;2:157-74.
[67] Tian W, de Wilde p. Uncertainty and sensitivity analysis of the performance of an air-conditioned campus in the UK under probabilistic climate projections. Automation in Construction. 2011;20:1096-1109.
[68] Morton TA, Bretschneider P, Coley D, Kershaw T. Building a better future: An exploration of beliefs about climate change and perceived need for adaptation within the building industry. Building and Environment. 2011; 43: 1151-1158