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Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards

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ABSTRACT

In view of the warming climate, there is increasing concern about the likelihood of overheating inside UK buildings that are not mechanically cooled. A number of studies are examining this matter, of which the DeDeRHECC project is one. The recent availability of the UKCP09 future climate data projections has acted as a stimulus to such work. This paper illustrates how field measurement, thermal modelling and the generation of current and future typical and extreme weather years, can be used to provide a picture of the resilience of buildings to climate change. The unified framework for assessing both measurements and current and future predictions that is offered by the BSEN15251 thermal comfort standard is a crucial component. The paper focuses on internal temperatures during the day and at night in wards within the tower building at Addenbrooke's hospital, which has a hybrid ventilation strategy. The maintenance of thermal comfort in such spaces is critically important and installing air-conditioning in response to climate change is expensive and potentially energy intensive. Fans appear to be a simple retrofit measure that may substantially improve the wards' resilience to climate change even in extreme years. Whilst healthcare provides the back cloth, the methodology developed has a much wider utility for assessing thermal comfort in buildings in the current and future climate of the UK.

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1. Introduction

There is increasing debate about the impact that climate change may have on the internal summertime temperatures in UK buildings because future summers are likely to be both warmer and drier and there is likely to be an increase in the occurrence of extreme temperatures. Elevated temperatures in homes are of particular concern and this may be exacerbated as insulation levels increase. Future conditions in non-domestic buildings are also a concern, the owners and operators of buildings are becoming increasingly interested in the resilience of their existing stock and the clients for new buildings wish to know how resilient the proposed designs are likely to be.

In common with other countries within temperate climate zones, the great majority of UK buildings are passively cooled, especially through the use of operable windows and, in non-domestic buildings, mechanical ventilation. For such a building stock, knee-jerk reactions, especially those that leads to, or even encourage, the installation of mechanical cooling or air-conditioning, must be avoided: this is expensive and could simply exacerbate the climate change problem by increasing energy demand. What is needed is a systematic and rational approach to identifying buildings that are thermally susceptible to the changing climate.

Thermal susceptibility will differ with geographical location, the building type and its function, and the vulnerability of the occupants to elevated temperatures. The need, or not, for adaptation needs to be reliably predicted, a pallet of refurbishment measures for different building types developed, and the sequence of appropriate interventions determined.

These matters are at the heart of much current research in the UK, notably within the Research Councils UK, Living with Environmental Change programme [1] and work funded through the Engineering and Physical Sciences Research Council's (EPSRC), Adaptation and Resilience to Climate Change (ARCC) programme [2]. This programme, gains much momentum from the recently produced climate change scenarios which, together with a weather generator and algorithms developed by others, enables the generation of hourly weather data at a 5 km by 5 km grid resolution [3]. Typical and extreme future weather data suitable for used in

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dynamic thermal models of buildings and in models used in other areas of research, such as flood risk assessment, crop growth studies, etc can be generated.

The ARCC-funded project reported here concerns the Design and Delivery of Robust Hospital Environments in a Changing Climate (DeDeRHECC). The project is supported by four Healthcare Trusts that have provided access for the monitoring and surveying of 111 spaces in 9 buildings, some 180 data points logged continuously over a two year period. All but 7% or so of the spaces were free-running in summer, i.e. they were not air-conditioned or otherwise mechanically cooled. Free-running spaces are the norm in UK hospitals.

Hospital buildings in the UK are particularly interesting and demanding from both the climate change adaptation and climate change mitigation perspectives. Concerning mitigation, the UK NHS is very large, occupying some 14,040 premises, about 1% of the UK's non-domestic buildings, and it is responsible for nearly 3% of all UK emissions and 30% of public sector emissions [4]. Thus the National Health Service (NHS), the Department of Health (DoH) and the Trusts that run healthcare services have a major role to play in helping to achieve the UK GHG reduction targets. Building refurbishment strategies that will reduce energy demand are of central interest in the DeDeRHECC project (see e.g. [5]).

Concerning adaptation, during periods of high ambient temperature, hospitals are expected to provide a safe haven for those at large who are suffering, especially during heatwaves [6]. Thus, it is precisely at times when temperatures are high that hospitals harbour the greatest concentration of vulnerable individuals. The thermal comfort of sick and vulnerable individuals as well as normal healthy occupants, during both typical and extreme weather conditions, must therefore be considered.

Refurbishment of the NHS stock is challenging, UK healthcare buildings are numerous and diverse in their constructional form, age and servicing strategy, although very little of this stock is air-conditioned: indeed, air-conditioning is avoided specifically because it is expensive to install and operate [7]. In hospitals, control of infection is a major consideration and this also places a major, but actually rather ill-defined, constraint on modifications that can be made to buildings, their services or their operating regimen. Also, the logistics of refurbishment are complex because UK hospitals strive for a high bed utilization, e.g. in the three months to October 2010 the utilization in the Leicester NHS Trust was, depending on the Department, 79–100% [8], and these patients are very susceptible to noise, dust, etc due to refurbishment work. Thus the need for, and method of, refurbishment to increase climate resilience is likely to be very different across the stock and the opportunities for such work, and the time available in which to do it, is likely to be constrained.

Refurbishment must also avoid increased energy use, which argues against air-conditioning. Indeed, the introduction of full mechanical systems into a building that is free-running can be particularly expensive and disruptive. Quick, light touch and non-intrusive strategies are highly desirable. A companion paper [5] examines the practicality of a number of active and passive low-energy refurbishment measures for improving the resilience of hospital wards. Here the simple expedient of introducing personal or ceiling fans to provide comfort with little increase in energy demand, is briefly considered.

The biggest challenge with low-energy refurbishment is the provision of thermal comfort for all hospital occupants during hot weather and such weather will be more frequent as the climate warms. The diverse occupants of hospital have differing thermal comfort requirements, most important are the patients but others include clinicians and nursing staff, support staff (administrators, cleaners, etc) and visitors. At times, any or all of these may occupy the same space, for example a hospital ward. Whilst patients may be very sensitive to abnormally high or low temperatures (being old, or sick or having impaired thermoregulatory systems) other occupants will have more 'normal' thermal requirements and expectations, but they will inhabit the hospital for many more days (or years) than most of the patients. An examination of prevailing thermal comfort standards and their usefulness for evaluating summertime temperatures in hospital wards, especially those that are not mechanical cooled, is a key aspect of this paper.

The tower at Addenbrooke's hospital in Cambridge, UK provides the vehicle for examining the applicability of thermal comfort standards and the performance of fans. The origin of the building and its geometry and construction is fully described elsewhere [5]. Internal temperatures were measured in the wards and nurses stations during a 46 day period in the summer of 2010. At the start of the period, July, a Level 2 heatwave was declared, although a full heatwave did not materialise [9]. Likely future temperatures and the consequential thermal comfort of occupants, with and without fans operating, are predicted using a calibrated dynamic thermal model.

The tower building has a simultaneous hybrid ventilation system, that is, the mechanical system run permanently and in tandem with the manual system – operable windows. This paper is thus complementary to [10] that examined the future performance of refurbishment measures in passively ventilated ward spaces using the same comfort criteria.

Whilst hospitals are the spring board for the work, it should be of much wider interest, as it leads to a methodology that can be used in many free-running building types to assess internal thermal comfort, overheating risk and resilience to climate change.

2. Methodology

One aim of the DeDeRHECC project, which is the nub of this paper, is to develop a methodology for assessing the resilience to climate change of UK healthcare buildings. The methodology must enable credible models to be built that can predict the internal conditions in current and future, typical and extreme, climatic conditions and enable the widest possible range of innovative refurbishment and low-energy cooling strategies to be evaluated.[1]

A five stage methodology is envisaged. Firstly the geometry, construction, servicing strategy and environmental control of the spaces is determined. This requires the study of archive drawings, field measurements and observations, and interviews with facilities management and other staff. Secondly, temperatures are recorded in target spaces to determine the internal temperatures and, when and where possible, air flow rates, CO_2 levels, window opening strategies etc. Although this work focuses on summer conditions, temperatures are recorded throughout the year.[2] These data are archived cleaned and key parameters produced. Thirdly, the temperatures are compared with the appropriate thermal comfort standard to assess the extent to which the spaces are, or are not, delivering thermal comfort for the weather conditions that prevailed during the monitoring period. Fourthly, a model of the space(s) to be assessed is built within a dynamic thermal model. This model is then 'calibrated' using the weather data recorded during the monitoring period with the monitored internal

[1] Comfort conditions might be controlled by adjusting air temperature of course, but also by controlling air speed, using fans or directional diffusers, or changing the radiant temperatures using heated or cooled ceiling panels - a fairly common strategy in modern hospitals. In the context of fabric refurbishment, the impact of shading on incident short wave radiation is also important.

[2] A parallel study is investigating energy demands in hospital spaces.

temperatures as the basis for model/data comparison. Finally, the calibrate model is used to predict the internal temperatures in the space, both as is, and after refurbishment, for the current climate and the possible future climates at the building's location. Performance under both typical and extreme conditions is of interest.

The credibility of the methodology hinges on the validity of the thermal model, a suitable approach to assessing thermal comfort and the selection of the current and future climate data. It is these matters that are the main concern of this paper.

Whilst the Addenbrooke's tower in Cambridge, with or without a simple retrofit, ceiling fans, is used to develop the methodology, it has already been used to assess the climatic resilience of Nightingale wards located in the North of England [11] and to evaluate a range of fabric and energy-system refurbishments. The methodology will be refined as other buildings operated by the four Trusts are assessed.

3. Thermal comfort evaluation for healthcare buildings

3.1. Simple overheating criteria

The development, in the late 1980s, of dynamic thermal models capable of predicting the hourly internal temperatures in buildings required the development of criteria for assessing whether a building was likely to overheat. This was particularly important for free-running buildings; which the CIBSE Guide A defines a building that, at the time in question, doesn't consume energy for heating or cooling. Elsewhere, e.g. in the ASHRAE Standard 55 [12], the term 'naturally conditioned' is used.[3] In the late 1980s, there was little field data that related internal temperature to perceived thermal comfort and so the criteria developed were pragmatic propositions developed by academics and engineering professionals based largely on 'engineering judgement'. Reviews by Eppel and Lomas [13] and Cohen et al. [14]; revealed four different sets of criteria. A Dutch method used a 'double pass' system - that buildings should have no more than 5% of working hours over a dry-resultant temperature (DRT) of 25 °C and no more than 1% of hours over a DRT of 28 °C.[4,5] A criterion used in the UK government-funded Passive Solar Programme placed a limit of 3% of working hours on the occurrence of a DRT of 27 °C. Design Note 17, which concerned the design of schools, stated that 10 days over a DRT of 27 °C[6] is a 'reasonable predictive risk'. Finally, and most interestingly, a standard used in the Zurich canton of Switzerland limited the degree.hours above a threshold temperature - a threshold that varied from 24 °C for ambient temperatures of 12 °C or less up to 28 °C when the ambient temperature exceeded 20 °C with a linear increase in the threshold temperature between these limits. By way of context, a DRT of 28 °C would, using steady state comfort theory [17] lead to approximately 30.5% of normally clad (1Clo) sedentary (1Met) occupants being dissatisfied; but just 7% dissatisfied if lightly clad (0.5Clo) [18]. In the late 80s, the CIBSE Guide A [19] contained no firm criteria although field work by Humphreys was presented which showed that, in free-running buildings, internal temperature preferences increased with ambient temperature. By the 1999 edition, Guide A was proposing a 5%/25 °C DRT criterion [20]. The works of Eppel and Lomas and Cohen et al. showed that the choice of criterion can have a marked influence on building design, such as the allowable window area before overheating is predicted to occur.

The purpose of this short review is to emphasise that, from the very beginning: although there were various criteria, they were broadly consistent in placing an upper threshold value of 27/28 °C and permitting a small number (or percentage) of occupied hours to exceed this; where defined, DRT was invariably used as the internal temperature metric, which for most practical purposes is identical to the operative temperature (OT) that is today's preferred metric[7]; the criteria related to design prediction and not performance in use; the criteria relate to all occupied hours, with no explicit consideration of spaces for sleeping; there was emerging evidence that preferred temperatures increase with ambient temperature in free-running buildings; and, importantly, compliance, or otherwise, with these criterion as determined by modelling in conjunction with weather data *typical* of the locale – be that a Test Reference Year (TRY) (e.g. in the UK) or a Typical Meteorological Year (e.g. in the USA).

The idea of using extreme years to judge compliance against these same criteria, which is a uniquely UK approach, and which had nothing to do with climate change when introduced, was first mooted, as far as the current authors can tell, in a document called 'The energy efficient office of the future' [21]. The document gives no theoretical or experimental basis for the proposal, it contains no reasoned critique of the (then) prevailing practice (as noted above) and there was no testing of the design consequences of using an extreme year. The extreme year proposed was to be the third hottest year of 20 as determined by the "average daily mean temperature (using June, July and August only)". This was subsequently revised to the average temperature for April to September inclusive, following work by [22]; and this remains the basis for Design Summer Year (DSY) selection (see below). The CIBSE Guide J [23] published TRY and DSY data for three UK sites in 2002 and suggested the use of a DRT 5%/25 °C overheating criterion. Today, Guide J contains such data for 14 UK sites but none are close to Cambridge [24]. The use of extreme years for overheating assessment, and the method of selecting such years, has a strong influence on the approach taken by UK building energy researchers when developing future weather years for use in simulation models (see below).

The design criterion used most often today in the UK is that stated in the CIBSE Guide A [25] that "*during warm summer weather 25 °C is an acceptable temperature*" and for offices, schools and the living areas of dwellings, the overheating criterion is "*1% annual occupied hours over operative temperature of 28 °C*"; the criterion is to be used in conjunction with a DSY. Healthcare buildings are not explicitly mentioned in connection with the criterion. Regarding buildings in use, the Guide gives a brief summary of the limited available evidence. For non-air conditioned offices and schools the 28 °C/1% criterion is restated and, of interest for this paper, the Guide notes that local fans that increase air speed can be equivalent to reducing the OT by 2 K.

Turning to hospitals, the internal conditions *for design purposes* are given in DoH Health Technical Memorandum HTM03-01 [7], which gives the range of internal temperatures '*over which the temperature may float*' as 18–28 °C for single and general wards with

[3] The Addenbrooke's Tower is free-running during the summer when the external temperature exceeds 20 °C as the heat to radiant ceiling panels and to the ventilation air is turned off.

[4] The standard also considered whether relative humidity exceeded 60% or not.

[5] Modelling work [13–15] each using different building types, all noted that the 5%/25 °C part was more difficult to satisfy than the 1%/28 °C part, rendering the latter redundant.

[6] The current guidelines for schools in BB101 [16] give three criteria of which two must be satisfied, one of these is that "there should be no more than 120 h when the air temperature in the classroom rises above 28 °C".

[7] For air speeds less that about 2 m/s and where radiant and air temperatures differences are less than 4 K, operative temperature is virtually identical to the average of the air and radiant temperature, which is the dry-resultant temperature. As air speeds increase, e.g. through the use of fans, air temperature becomes relatively more influential. Operative and dry-resultant temperature account for convective and radiant heat exchange with the human body.

supply-only ventilation (as is the case for the Addenbrooke's tower). The memorandum notes that mechanical '*cooling is very expensive*' and so '*calculations and thermal modelling should be undertaken to ensure that, during summertime, internal temperatures in patient areas do not exceed 28 °C (dry-bulb) for more than 50 h per year*'; which equates to about 0.6% of occupied hours as wards are virtually permanently occupied (cf. the CIBSE 1% limit). The weather data to be used in conjunction with the criterion is not stated, there is no specific comment about nighttime temperatures, and nursing stations are not explicitly addressed. Neither does the memorandum make any comment about the use of fans, or any other low-energy comfort cooling devices. An earlier paper provides a critique of HTM03 and this overheating criterion in particular [10]. The use of dry-bulb temperature, rather than OT is unusual and it means that radiant heating and cooling, and cooling by air movement, be these achieved actively or passively, cannot be properly recognised.[8] This paper focuses on wards and in this context HTM03, notwithstanding its weaknesses, is clearly important and so is used both as a benchmark for considering the measured temperatures and for the evaluation of predicted internal temperatures.

The question of nighttime thermal comfort, and more generally comfort whilst sleeping, is important in a hospital context. A brief literature review revealed the complexity of providing a criterion, not least because thermal comfort, as conventionally framed, "that condition of mind that expresses satisfaction with the thermal environment" is inapplicable during sleep. Sleep studies thus rely on measurements of, e.g. rates of heat loss, skin temperature, sleep patterns and nighttime awakening, rather than satisfaction surveys. In hospitals, patients may well be asleep due to illness, their medication, post-trauma recovery etc, so criteria framed by studies of healthy individuals in 'normal' environments need to be treated with caution. For homes, the CIBSE Guide [25] notes that "*thermal comfort and quality of sleep begins to decrease if bedroom temperatures rise much above 24 °C*" (at these temperatures sleepers are likely to be covered by a single sheet) and that "*bedroom temperatures at night should not exceed 26 °C unless ceiling fans are available*" (note especially the reference to fans). An overheating risk criterion is given: there should be no more than "*1% of occupied hours over an operative temperature of 26 °C*", which is applied in conjunction with a DSY. In the work reported here, the CIBSE criterion is used as a benchmark for considering the predicted nighttime temperature, but little weight is given to this assessment.

3.2. Adaptive criteria

Natural and hybrid ventilation predominates in healthcare buildings, and it has long been known (e.g. [26]), that occupants' thermal responses in free-running spaces differs from that of the occupants of conditioned (i.e. heated and cooled) spaces. The internal conditions in such buildings tend to drift with the ambient conditions, as do the thermal expectations of people. Thus people become well adapted to the thermal environment in free-running buildings and find them comfortable. Departures from these expected temperatures provoke thermal discomfort, for example over-cooled buildings in summertime. The provision of spaces that provide the customary thermal environment for the climate, season and culture is important. Most UK hospital patients, staff and visitors will be adapted to temperatures in free-running buildings because most will live and work in such spaces. Increasingly, hospitals seek to minimise overnight stays so adaptation of patients (and visitors) to hospital conditions which differ will be limited.

Extensive field measurement campaigns have been undertaken that supported the concept of thermal adaptation.[9] These have led to the development of adaptive thermal comfort standards in which the threshold of acceptable indoor temperature, and all adaptive standards use OT, increases as the external ambient temperature increases. The salient point here is that the adaptive standards are based on field surveys so inherently account for the plethora of factors that influence thermal comfort. As data is drawn from across the globe, including from countries that are warmer than in the UK or projected future UK, the adaptive standards are inherently applicable to a very wide range of UK weather years. Further, being based on measured data, the standards derived are inherently applicable to buildings' performance in use, as well as to the assessment of predictions. All this is in stark contrast to the simple criteria described above.

We would expect that, as the UK climate warms, people will adapt and become accustomed to the new conditions. Thus, when trying to predict whether the occupants of free-running buildings will be comfortable in the UK climate of the future, it seems entirely sensible to use adaptive comfort criteria, rather than the simple, static, non-climate sensitive criteria described above. In the context of the DeDeRHECC project, and for other work that is trying to predict comfort in the climate of the future, adaptive temperature criteria demand serious consideration.

The ASHRAE 55 standard [29], which owes much to the work of de Dear and Brager [30], defines the internal thermal conditions for normal healthy adults. The long-established ASHRAE thermal comfort envelopes form the focus of the standard, but since the 2004 version [12], an 'optional method' has also been provided for 'naturally conditioned' spaces, i.e. those that are not mechanically cooled, i.e. free-running. Mechanical ventilation with unconditioned air is permissible but spaces must be primarily regulated by occupants' opening and closing of windows. The method applies when occupants are engaged in near-sedentary activity and free to adapt their clothing. Clearly, there is conflict here with the status of some patients. The method provides an allowable indoor OT envelope with upper and lower bounds that increase with the *mean monthly* ambient air temperature (T_{mm}) at a rate of 0.31 K per K; the envelope is applicable when $10°C < T_{mm} < 33.5$ °C. A narrower envelope, in which the upper and lower boundaries are 5 K apart, indicate 90% of occupants will be satisfied (Fig. 1) and a wider envelope, with boundaries 7 K apart, gives 80% acceptability. The standard provides a mechanism for accounting for fans but not in association with the optional method.[10]

The CIBSE Guide A [25], presents an envelope of acceptable indoor OT, which increases with the *exponentially weighted running mean* of *the daily mean* ambient air temperature (T_{rm}) at a rate of 0.33 K per K. The upper and lower bounds are 4 K apart and are applicable between limits of $8°C < T_{rm} < 25$ °C (Fig. 1). The use of T_{rm}, rather than T_{mm} as in the ASHRAE method, recognises that adaption takes place over a time scale of days and not months with more recently experienced temperatures being more influential. The guide is applicable to free-running buildings, in which occupants may exercise environmental control, e.g. via operable

[8] Other temperature-related factors are also important in hospitals, notably, that at higher temperatures, e.g. above 25 °C, some pharmaceutical products may start to degrade, and some patients will have conditions that demand special attention to their thermal milieu. These matters are without the scope of this paper.

[9] Notably the work within the EU SCATS project [27] and a global data base of 21,000 measurements, primarily from office buildings, which underpins the ASHRAE adaptive standard [28].

[10] The provision is offered in conjunction with the traditional ASHRAE thermal comfort envelopes.

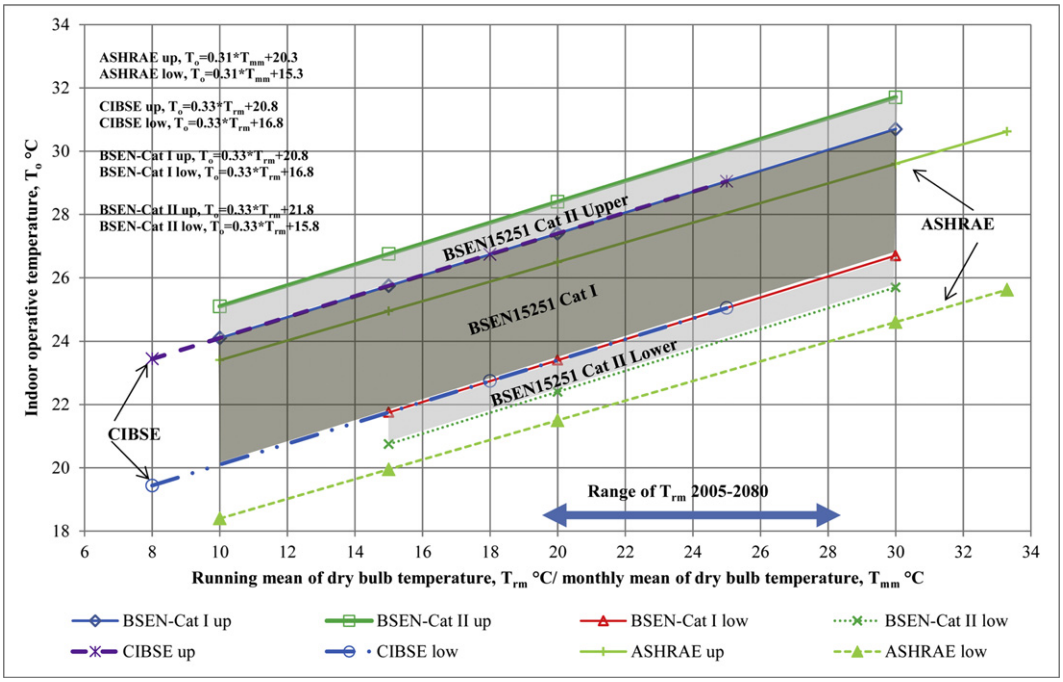


Fig. 1. Comparison of adaptive thermal comfort standards: equations, envelopes, boundaries and limits of applicability.

windows, the use of fans, or by changes to clothing, and it is implicit, but not stated, that the envelope is relevant to normal healthy individuals. The percentage satisfaction provided by environments that fall within the boundaries is not stated (but see below). It is stated that OT drifts a little above the upper boundary might attract little attention, but an OT of 2 K or more above would be likely to attract complaint.

The new European (and so British) Standard BSEN15251 [31] offers a more holistic approach than the ASHRAE method and, as a national and EU standard has precedence over the CIBSE method, (but fortunately it has envelope boundaries identical to those of the CIBSE method, Fig. 1). As the standard's title indicates, it is explicitly applicable to both '*design and assessment of … thermal environment*' and both purposes are explained in the standard. Like the other adaptive approaches, BSEN15251 provides an envelope for acceptable OT that increase with T_{rm}, in this case at a rate of 0.33 K per K over the range $10 < T_{rm} < 30$ °C and $15 < T_{rm} < 30$ °C for upper and lower bounds respectively; where T_{rm} is defined identically to the CIBSE method.[11] Importantly, the standard's scope includes '*hospitals*', and '*methods for long term evaluation of the indoor environment*', and the envelope width depends on the 'Category' of the space under consideration (Fig. 1). The most stringent is Cat I: '*High level of expectation* [which] *is recommended for spaces occupied by very sensitive and fragile persons with special requirements like, handicapped, sick, very young children and elderly persons*'. This category has the narrowest envelope (which is identical to the CIBSE envelope) and will yield less that 6% of normal health persons dissatisfied. Cat II is the '*normal level of expectation and should be used for new buildings and renovations*', less than 10% dissatisfied, and Category III: '*acceptable, moderate level of expectation and should be used for existing buildings*', 15% dissatisfied. Suggestions for the acceptable daily, weekly and annual deviations outside the chosen category limits are provided for *measured* temperatures. These equate to exceedences of either 3% or 5% of occupied hours (cf. CIBSE Guide A recommendation noted above), although other methods, e.g. a degree.hour approach, are also offered. The standard also offers a mechanism by which the allowable temperatures might be adjusted to account for the impact of occupant controlled fans.

The Standard states: (1) that it is "*valid for office buildings and other buildings of similar type…with mainly sedentary activities…-where there is easy access to operable windows and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions*" [authors' underlining]; (2) '*There shall be no mechanical cooling*' but '*Mechanical ventilation with unconditioned air (in summer) may be utilized but opening and closing of windows shall be of primary importance as a means of regulating thermal conditions in the space. There may in addition be other low-energy methods of personally controlling the indoor environment such as fans, shutters, night ventilation, etc.*' Of these statements, it is the first regarding buildings similar to offices that is most at odds with the spaces in hospitals of interest to this paper, although as noted elsewhere the standard indicates it's applicability to hospitals and to spaces with sick persons. Although the standard notes its applicability to bedrooms, at night individuals are inactive (<1Met) and they have a reduced capacity to take adaptive actions without disrupting sleep. In this work therefore nighttime temperatures are distinguished from daytime temperatures.

The standard states that the space to which each comfort category applies is '*up to national regulations or individual project specifications*'. Here it is suggested that Cat I might apply to hospital wards, Cat II to staff areas, consultation and administrative offices and Cat III to public and circulation spaces. The standard does not place strict limits on the frequency at which the Category limits may be exceeded, although exceedences of 3–5% of hours are suggested, along with other methods of defining exceedences. Further, the time period over which the exceedence is considered can be daily, monthly, seasonal or yearly. The key point here is

[11] Although Olsen, in his paper on the philosophy of the method, [32] uses 'weekly running mean outdoor temperature', the Standard itself has as its *x*-axis the 'running mean of daily outdoor temperature', and this is used in the paper.

Table 1
Comparison of internal air temperatures measured between 1st July and 15th August, 2010, with CIBSE and HTM03 overheating criteria.

Level	Space	Maximum temperature °C (24 hours)	Minimum temperature °C (24 hours)	Mean daytime temperature °C (7:00 to 20:00)	Mean night time temperature °C (21:00 to 6:00)	Maximum diurnal range (K)	Hours over 25°C (24 hours)	Hours over 28°C (24 hours)	Hours over 24°C (21:00 to 6:00)	Hours over 26°C (21:00 to 6:00)
6	Multi-bed 6MB7	28.4	21.9	25.3	24.6	4.6	535 (48.5%)	6 (0.5%)	328 (71.3%)	43 (9.3%)
	Nurse station 6NS	29.3	24.4	27.1	26.4	3.6	1098 (99.5%)	110 (10%)	460 (100%)	339 (73.7%)
8	Multi-bed 8MB10	28.5	21.4	25.0	24.6	6.4	493 (44.7%)	3 (0.2%)	338 (73.5%)	38 (8.3%)
	Multi-bed 8MB4	28.1	21.2	25.3	24.7	6.6	581 (52.6%)	1 (0.1%)	350 (76.1%)	17 (3.7%)
	Nurse station 8NS	29.1	23.9	26.1	25.9	3.3	990 (89.7%)	15 (1.4%)	459 (99.8%)	205 (44.6%)

Dark Grey: Day time criterion limit exceeded.
Light grey, night time guidance exceeded.
Total number of hours: 1104 (46 days). Total number of night time (21:00 to 6:00) hours: 460.

that the standard provides a solid framework for thermal comfort assessment but assignment of spaces to thermal category and the permissible overheating risk can be decided by others: such as the DoH.

The three standards present very similar envelopes of thermal acceptability (Fig. 1) but BSEN15251 has advantages when trying to establishing a framework for assessing the indoor temperatures of free-running buildings, and hospital buildings in particular: it explicitly accommodates both performance in use and predicted performance, enabling both to be compared in a similar way; it has a range of applicability (up to T_{rm} of 30 °C) which covers even the temperatures found in extremely hot years up to the 2080s[12] (Fig. 1 and Table 2); it discriminates between spaces used for different purposes; and it provides the opportunity for the NHS, or others, to define the applicability of the category boundaries and the allowable deviations of temperature outside these boundaries. Given all this, the Standard was used as the primary mechanism for assessing the internal comfort in the work reported here. More generally, it will provide the backbone for the analysis of spaces in all the hospitals studied in the DeDeRHECC project. By working with the standard it is hoped that suggestions for its further refinement will emerge.

4. Weather data measured and for modelling

The matter of selecting weather data was important as the approach used would be followed throughout the DeDeRHECC project. Three types of hourly data usable by dynamic thermal models were needed: a. weather data for the period during which internal temperatures were monitored; b. a TRY and DSY representing the current climate of Cambridge, i.e. the 2000s; and c. weather files representing the climate of the future.

Weather data for the periods during which the hospitals were being monitored are derived, in general, from either existing weather stations or stations erected specifically for the project. For the Cambridge site, hourly ambient temperature (T_a) was gathered at the Cambridge University Computer Science Department, close to the centre of Cambridge, just 4 miles NNW of the hospital site. Various sites were investigated to obtain the other parameters, but ultimately these data were taken from the Meteorological Office station at Bedford. This site produced all the parameters necessary to create a simulation model weather file for the complete year (2010). The building research team at Exeter University generated the weather file in which the diffuse solar radiation, global solar radiation and direct solar radiation were derived from Bedford cloud cover as explained in CIBSE TM48 [33]. The other parameters such as dry-bulb temperature, wet bulb temperature, relative humidity, wind velocity, wind direction and pressure were taken directly from the observed data. The number of hours above ambient temperatures of 25 °C and 28 °C in this weather file are shown in Table 2.

Unfortunately, none of the CIBSE weather year sites [24] were sufficiently close to Cambridge to provide realistic data. Therefore TRY and DSY files for the 2000s, were created by the Exeter team from the 25 years of hourly data that was available from the Bedford station (1980–2004). Any missing data were added. From this a complete hourly data set, the 2005TRY, was generated using the standard CIBSE method as described in [34]; that is, by chaining the most average January to the most average February etc and then smoothing the joins. Most average is determined by generating the

[12] The calculated maximum running mean temperatures for the derived typical and extreme years (see Section 3) fall in June, July or August and are, for the TRYs & DSYs: 2005–19.5 °C & 22.9 °C; 2030s–21.1 °C & 24.4 °C; 2050s–21.5 °C & 26.6 °C; and 2080s–22.6 °C & 28.6 °C.

Table 2
Characteristics of the year 2010 and typical and extreme years for Cambridge.

Year[a]	Ambient hours over		Maximum value of		
	25 °C (h)	28 °C (h)	Running mean temperature (°C)	Cat I upper threshold (°C)	Cat II upper threshold (°C)
2010	52	4	19.7	27.3	28.3
2005TRY	33	2	19.5	27.2	28.2
2005DSY	137	44	22.9	28.4	29.4
2030sTRY	204	37	21.1	27.8	28.8
2030s DSY	577	219	24.4	28.9	29.9
2050sTRY	309	62	21.5	27.9	28.9
2050s DSY	788	341	26.6	29.6	30.6
2080sTRY	404	126	22.6	28.3	29.3
2080s DSY	1093	566	28.6	30.2	31.2

[a] 2030s, 200s and 2080s climate as created by the UKCP09 weather generator.

cumulative distribution function for the dry-bulb temperature, global solar radiation and wind speed and then calculating the Finkelstein-Schafer (FS) statistic for each distribution [35]. This statistic chooses months with less extreme values that have a cumulative distribution closest to that of all the years. The weighted sum[13] of the FS statistics of the three variables is then calculated to identify the typical month; the process is repeated for all 12 months. The 2005DSY was also selected using the standard CIBSE approach, that is, by simply selecting the year that is third hottest based on the average dry-bulb temperature from April and September; for the Bedford data set this was 1997. It can be seen (Table 2) that the 2005TRY has a rather similar number of hours above 25 °C and 28 °C to the year 2010; in fact, the similarity extended across all hours from 20 °C to 28 °C. Thus the year of monitoring would seem, quite fortuitously, to be rather typical of the current climatic conditions in Cambridge.

The publication of the UK Climate Projections [3] enables climate data for future years to be created for different global emissions scenarios, using a weather generator. These future weather projections hinge on knowing the daily precipitation across the UK and the prediction of a 'change factor', for any future year, which is dependent on the assumed future meteorological conditions. The weather generator produces nine variables that describe the daily weather and from these, using relationships derived from observations, seven hourly variables are disaggregated, these include dry-bulb temperature and solar radiation[14] (see [36] and [37]). The UKCP09 weather generator produces weather for different future time points in decadal time slices from the 2020s up to the 2080s for different emissions scenario assumptions and, most importantly, it provides output on a 5 km grid. This excellent spatial resolution, which inherently accounts for topography and land cover, e.g. urban or rural, obviates the problem of identifying a suitable weather site close to buildings of interests.

From the data produced by the weather generator, research groups in the UK have developed alternative methods of creating complete hourly weather files for use by simulation models. For the DeDeRHECC work, the weather files were produced by the Prometheus project team at Exeter University using the approach described in [38]. Essentially, their approach involves using algorithms and statistical relationships to generate hourly wind speed and direction, air pressure and cloud cover, to supplement the generator's output. Then the TRYs and DSYs are identified from within the 100 sets of 30 year long hourly data produced by the weather generator to represent a chosen decade, e.g. the 2050s[15] (see [38]). Each 30 year string represents one possible future climate condition and the years in it the natural year-on-year variability. Each of the 100 sets represents a different possible realisation of the future climate for the assumed emissions scenario – future climate prediction is of course uncertain.

To create a single TRY, the most average months are selected from within each 30 year string using the standard approach (see above), which gives 100 possible TRYs, then the 100 Januarys and the 100 Februarys etc, are ranked based on their mean monthly temperature and the 50 percentile months selected. Then the 50 percentile January is chained to the 50 percentile February etc, and the interfaces smoothed (see [34]) to give one TRY (the one used in this work at least[16]).

An approach compatible with that described above is also used to identify the DSY. Firstly, the fourth warmest year, based on the April to September average temperature, is identified from within the 30 year string (i.e. the 90 percentile year - the one for which only one year in ten is warmer). Then, the same procedure as for the TRYs is used, chaining the most average of the 100 Januarys, to the most average February, etc, to get the final DSY.

This method of generating TRYs and DSYs means that each month in the TRY is the most typical and each month in the DSY is the 90 percentile extreme. Thus, meaningful interpretation of the monthly, and not just the yearly, model predictions is possible. The characteristics of these future years are listed in Table 2. The rapid escalation in the temperature of the extreme years as time passes is apparent.

In this work, using the above method, the future weather for the 2030s, 2050s and 2080s, were generated, for the square 5km covering central Cambridge[17] assuming the global A1B, emissions scenario as described in the IPCC Special Report on Emissions Scenarios[18] [39]; which is the emissions track currently being followed. Further, this work uses 50 and 90 percentile probabilistic weather files for TRY and DSY respectively. In interpreting the results, it is therefore important to understand that the future could be even warmer than that which is assumed, or indeed cooler, but it was beyond the scope of this work to investigate the sensitivity of the results to different emissions scenario assumptions and probabilistic conditions. Importantly thought, the relative performance of alternative refurbishment options as the climate changes is likely to be robust.

In previous work looking at the impacts of climate change on naturally ventilated hospital ward spaces [10], future weather data for the medium-high emissions scenario A2 – called 'National Enterprise' had been generated using the UKCP02 data and a cruder approach to generating future weather files, based on 'morphing' [40,41]. In their work, Eames et al. [38] note that, this cruder approach produced compatible weather files to those using the UKCP09 approach and, for the same emissions scenario, very similar internal temperature predictions. The spatial resolution of the UKCP09 data is though, very much better.

[13] Here the three parameters were equally weighted.

[14] Daily precipitation, maximum and minimum temperature, sunshine fraction, vapour pressure, from these four other parameters are produced using standard formulae, relative humidity, direct and diffuse radiation and potential evapotranspiration (PET). The hourly values are precipitation, temperature, vapour pressure, relative humidity, sunshine fraction and direct and diffuse solar radiation.

[15] The 30 years are stationary with regard to climate change and vary stochastically to account for the natural variability of the weather. The 2050s is represented by a 30 year weather string running from 2040 to 2069, the 2030s and 2080s data is similarly defined.

[16] The Exeter team have generated different probabilistic weather years representing 10, 33, 50, 66 or 90 percentiles for both TRYs and DSYs.

[17] UKCIP 09 grid reference is 5500260.

[18] A globalized, technologically advanced world in which energy production includes a broad portfolio of fossil-fuel and non-fossil-fuel sources.

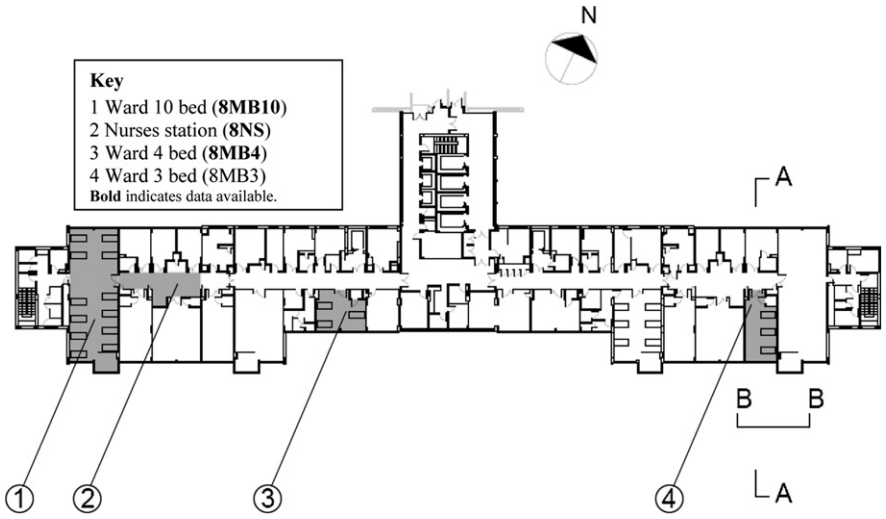


Fig. 2. Floor plan Level 8 Addenbrooke's Tower.

Finally, by way of context, Eames et al. [38] note that, the heat wave in Europe, in 2003, is estimated to be a one in a thousand event by the Meteorological Office's Hadley centre in the current climate, but will be typical of the summers of 2040s and in the 2080s, anomalously cool.

5. The Addenbrooke's tower

The Addenbrooke's tower remains largely as built in 1972 [5] with the 3rd to 9th floors that house the wards protruding out of the lower 3 level podium. Temperature monitoring equipment was installed in three wards and a nursing station on floor 7 (level 8) and also on floor 5 (level 6) (Figs. 2 and 3). The end wards, such as the 10 bed ward on level 8 (8MB10) are 18.3 m wide spanning the width of the tower. The wards in the end thirds, such as 6MB3, 6MB7 and 8MB3 are 10.2 m deep and in the central third, 6B1 and 8MB4 are 5.7 m deep. The nursing stations, 6NS and 8NS, occupy the core of the building. There are toilet blocks at the ends and around the lift block that stands off to the NW.

The low-emissivity double glazed windows ($U \approx 1.9$ W/m^2 K) run as a continuous ribbon at all levels on both main facades with uninsulated opaque panel below ($U \approx 2.1$ W/m^2 K) and insulated concrete above ($U \approx 0.5$ W/m^2 K). Even ignoring the heat bridging at the floor to outer wall junctions, this yields an area-averaged U-value of about 1.2 W/m^2 K. The windows in the lower 1.83 m are top-hung and operable, but restricted for patient safety to an opening of 100 mm. The upper windows (also 1.83 m tall) are fixed. In general, the window-to-floor area ratio on the SE side, which is most exposed to solar gains, is about 15% in the deeper rooms and as much as 35% in the shallower spaces.

The wards and treatment rooms in the tower are permanently ventilated using a simultaneous hybrid system, the operable windows, and air supplied from the central air-handling unit, which is pre-heated if necessary. There is no dedicated air exhaust route and so all delivered air escapes from the building either through the designed toilet (and other) exhausts, through windows and doors, or through other gaps in the fabric. The ventilation rate to the whole building was essentially unknown but had been designed to provide about 4 ach^{-1}; the flows to the individual

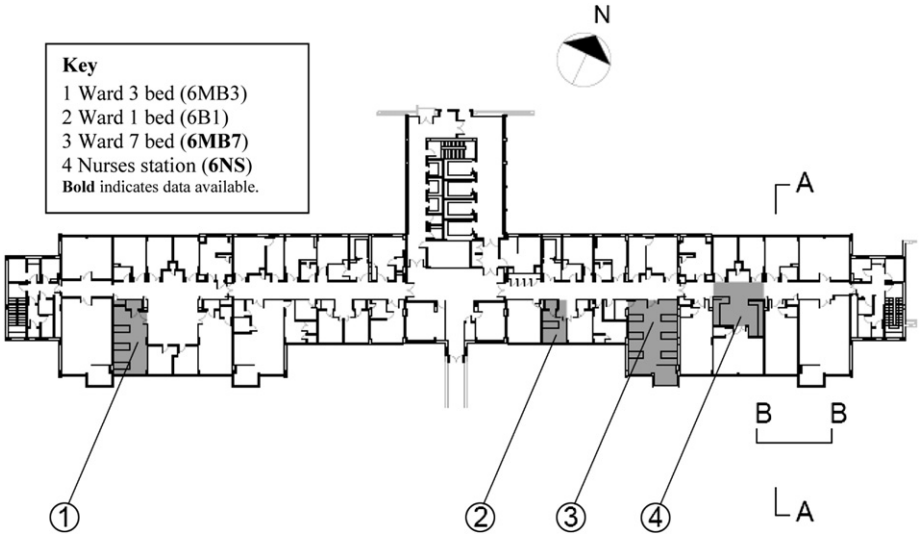


Fig. 3. Floor plan Level 6 Addenbrooke's Tower.

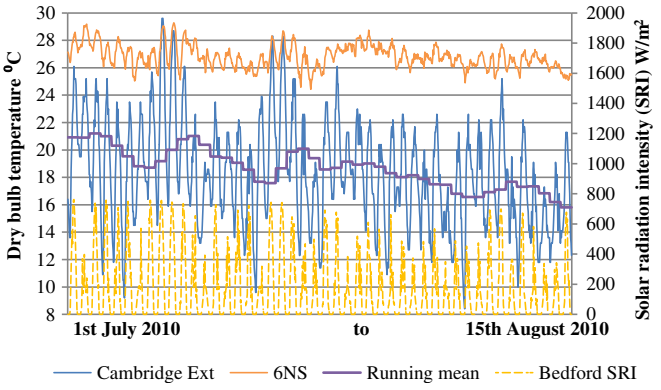


Fig. 4. Recorded internal and ambient dry-bulb temperatures, and total solar radiation in the Nurses station on level 6 (6NS).

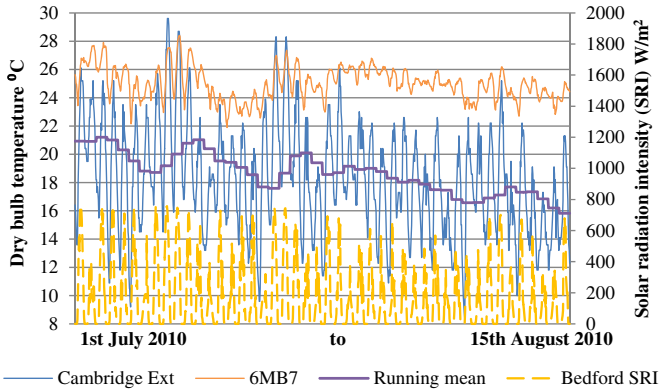


Fig. 5. Recorded internal and ambient dry-bulb temperatures, and total solar radiation in the 7 bed ward on level 6 (6MB7).

rooms were unknown. The nurses' stations have no dedicated ventilation; they just receive the air flowing back along the central spine to the extracts. All spaces and circulation areas are heated by a suspended radiant ceiling. Whilst the wards fall within the scope of the adaptive comfort standards, the nurses' stations, which do not have operable windows or other devices to admit ambient air, do not.[19]

Site visits provided an impression of the control strategy employed. Essentially, in winter, the ventilation air is heated to 18 °C but the set point was ramped down from 100% at an ambient temperature $T_a \leq 16$ °C to zero at $T_a \geq 18$ °C. The radiant panel heating set point was set at 30 °C in summer and 32.5 °C in winter. It was gradually ramped down from 100% when $T_a \leq -3$ °C to 60% at $T_a = 15$ °C and off at $T_a = 16$ °C. Thus, whenever the ambient temperature reached 18 °C, the building was in free-running mode and the wards therefore amenable to analysis by the adaptive standards. In practice however, the facilities managers adjust the set points throughout the year in response to occupant requests.

The site visits also revealed the limited provision for occupant control of the heating panels and the few thermostats that had been provided were clearly damaged. The insulation that had been located above the heated ceiling had been substantially dislodged during successive retrofits and in places completely removed. Thus heat, intended for the metal ceiling, warmed the concrete in the floors above causing uncontrollable heat gain. Likewise heat was lost from the hot water pipes into the occupied space.

The uncertainties about the internal heat gains, the lack of knowledge about how occupants used the windows, the uncertainty about air flow rates and the variability of the operating regimen, posed difficulties when trying to build a thermal model of the building and the spaces in it (see below). Such problems are not though special, either to the Addenbrooke's hospital tower, or to hospitals in general. In fact, uncertainties of this ilk abound within any older building and so models of them can only be, at best, a rough approximation.

6. Measured internal temperatures

6.1. Method of measurement

Accessing and monitoring spaces in hospitals proved challenging. There are concerns about occupant privacy, introduction of infection by the monitoring team, infectious agents trapping in the sensors, the need in some hospitals for sensors to be removable for infection control cleaning, the availability of staff to provide access to spaces, the need for sensors to be well away from areas of potential medical procedures, and, once installed, the potential for interference from occupants and repeat access difficulties for checking sensors and doing intermediate data downloads. Thus, when building access was gained, the wards chosen for monitoring were a compromise between the DeDeRHECC project ideals and the permissions that could be gained. Spaces monitored are indicated in Figs. 2 and 3, but unfortunately the sensors in three wards were lost entirely, 8MB3, 6MB3 and 6B1.

Monitoring of the Addenbrooke's Tower started in late June 2010, with data being available from 1st July 2010. Here data is presented up to 15th August (a run of 46 days, 1104 h) for 3 spaces on Level 8 (Fig. 2) and 2 spaces on Level 6 (Fig. 3). On level 6, the data consisted of measurements of the air temperature[20] in a multi-bed ward (7 beds, 70.3 m^2, code 6MB7, three measurements) and in the nurses station (26.6 m^2, code 6NS, one measurement) and on Level 8 in two multi-bed wards (10 beds, 126.3 m^2, 8MB10, two measurements, and 4 beds, 35.0 m^2, 8MB4, one measurement) and a nurses station (9.93 m^2, 8NS, one measurement). The Hobo U12-001 sensors were suspended from hangers stuck to the walls so they could easily be removed for cleaning. They were unshielded but out of direct sunlight. The loggers recorded spot values on the hour (as do the meteorological sites).[21] The loggers are quoted as being accurate to ±0.35 °C, and in pre-trial testing the installed loggers recorded to within 0.2 K of each other at normal room temperature.

6.2. Analysis of measured internal temperatures

The data recorded by each sensor was complete with no obvious outliers. In spaces with multiple measurements, there was a clear variation between the values recorded near the windows and those recorded nearer the central corridor, with temperatures near the windows being generally cooler, notably so at night, perhaps as a result of window opening. In 6MB7 the minimum temperature near the window was 1–1.5 K lower than near the corridor.

[19] The lack of heat recovery results in an extremely energy intensive building (see [5]). A rough calculation indicates that the ventilation heat loss is about 5 times the fabric loss at an air change rate of 3ach^{-1}.

[20] Given the type of sensor, the radiant heating and the necessary near-wall mounting, this only approximates dry-bulb temperature.

[21] Throughout this work both internal temperatures and meteorological data represents a spot measurement with the first value for day 1 (July 1st) being at 00:00 and the last at 23:00, and so on. Thus the 10 nighttime hours (from 21:00 to 07:00) are represented by the 10 values recorded at 21:00, 22:00 … 06:00.

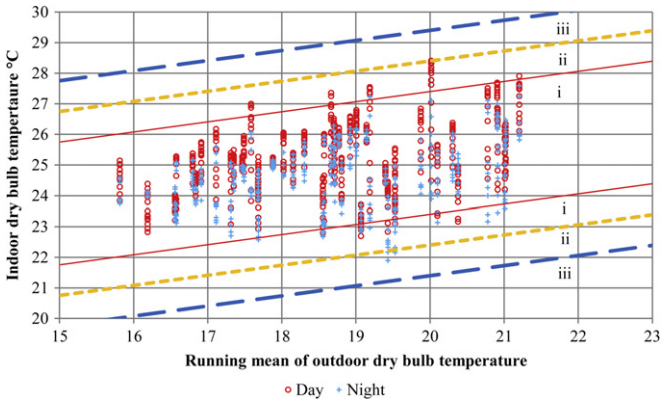


Fig. 6. Internal temperatures compared to BSEN15251 Category limits, seven bed ward on level 6 (6MB7).

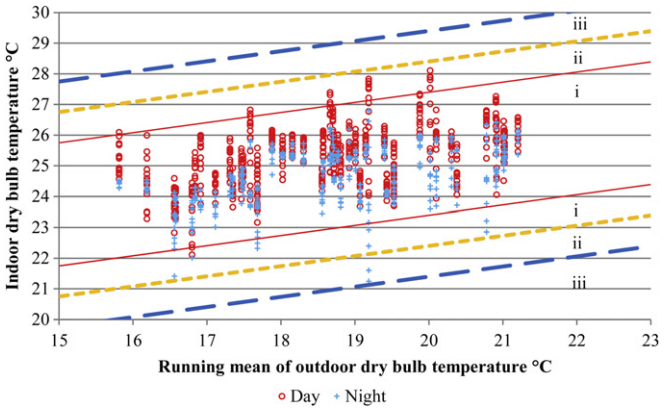


Fig. 7. Internal temperatures compared to BSEN15251 Category limits, four bed ward on level 8 (8MB4).

Throughout this paper internal temperatures are the average recorded value where multiple readings were taken (i.e. in 6MB7 and 8MB10). Thus minima and maxima relate to this spatially averaged value not the individual recorded maxima and minima.[22]

The internal temperatures recorded in 6NS and 6MB7 are plotted[23] in Figs. 4 and 5 along with the ambient temperature, its running mean (T_{rm}), and the solar radiation intensity. During two periods both the day and nighttime temperatures are high: 9th, 10th July and 19th, 20th July although neither period would be considered a heatwave under the NHS definition [6]. It is evident that both spaces are generally rather warm, being frequently above the 25 °C value that CIBSE notes is, for normal persons during warm weather, an acceptable temperature. On the hottest days the peak internal temperature is though a degree or two below that outside. The diurnal internal temperature variation is small, generally under 2 K but on warmer days up to c5 K. The nurses station 6NS runs at a particularly high temperature, being permanently between 24.4 °C and 29.3 °C. These high temperatures, are combined with a complete absence of occupant temperature control provision, and there are frequent complains from the nursing staff.

The nighttime temperatures clearly differ even on nights with rather similar ambient temperatures (cf. early morning of July6th and July 18th), which is a clear indication of the effects of opening, or not, the windows. Interestingly, in the shallow plan space 8MB4, the minimum recorded temperature, 21.2 °C, occurred on one of the warmest nights of the year, July 9th; on this day a Level 2 heatwave alert was issued[24]; in response to which, nighttime cooling by opening windows is a recommended procedure [6]. It seems ironic that the coolest nighttime temperature, a temperature that standards suggest is more conducive to good sleep, should occur on one of the hottest nights.

The other spaces behaved in a very similar way to those shown in Figs. 4 and 5; the key statistics are given in Table 1. All five spaces had mean daytime temperatures in the 25.0–27.1 °C range, mean nighttime temperatures from 24.6 to 26.4 °C, and between 44.7% and 99.5% of hrs over 25 °C. The nursing stations were warmer than the wards with 6NS having the highest day and night mean temperatures and 8MB10 the lowest. The nurses' stations also had smaller maximum diurnal ranges than the wards, especially those on Level 8 (Table 1). This is probably because the nurses' stations do not have operable windows were as the wards do, and these were left open on the hot the nights to provide welcome cooling (the maximum diurnal range was in Ward 8MB4, 6.6 K on 9th July), see Figs. 4 and 5.

Whilst the wards are generally warm, they all pass the CIBSE (28 °C/1% occupied hours) and HTM03 (28 °C/50 h a year) criteria. At night, all three wards had over 70% of hours with temperatures in excess of 24 °C and all three exceeded the nighttime overheating guidance (CIBSE, 26 °C/1% occupied hours) by a long way; with two of them having 8–9% of nighttime hours over 26 °C. These figures suggest that the warm conditions in the rooms might be consistently depriving some patients of quality sleep, perhaps for many nights in a row.

The nurse stations, which sit in the core of the building, were considerably warmer than the wards (23.9–29.3 °C). At the station on level 6, 6NS, there were 110 h with temperatures in excess of 28 °C, i.e. 10% of the recorded hours, which, applying the HTM03 target temperature for conditioned spaces (28 °C), represents overheating. The design of the ventilation system, together with heat gain from hot water pipes running above the corridor ceiling, the degradation of the insulation mat above the radiant ceiling panels[25] and the broken local thermostats installed to control the ceiling heat output, all contributed to produce the high temperatures. There is no prospect of the nurses' conditions being ameliorated, e.g. by natural ventilation through operable windows or other means.

To operate the BSEN15251 method the daily running mean of the mean daily ambient temperature, T_{rm}, was calculated (see Fig. 5) and the measured temperature plotted against it (Figs. 6 and 7 for 6MB7 and 8MB4). Such plots produce a stack of 24 hourly values for each day; these have been split into day and nighttime values.[26] It is evident that in both spaces the internal temperatures generally rise with the ambient temperature (T_{rm}) and that daytime temperatures are generally within the Cat I limits. Small deviations above the Cat I upper limit occur at low, as well as high, ambient temperatures, which suggests that in winter thermal discomfort due to overheating is worth investigating. Deviations below the Cat I lower limit occur most frequently at night; which, as

[22] Spatial variations of spaces temperatures and, potentially, the measurement of window opening behaviour, may be studied in future work.

[23] For other plots see [5].

[24] Although heatwave temperatures did not materialise.

[25] This means that heat from the pipes connected to the panels can convect upwards and warm the concrete floor above. This stores the heat and eventually loses it by convection and radiation warming the spaces above.

[26] This separation is important because, although parts of BSEN15251 indicate that it is applicable to domestic bedrooms, at running mean temperatures over 22 °C the Cat I lower limit exceeds 24 °C, yet quality sleep is more likely below this limit [25].

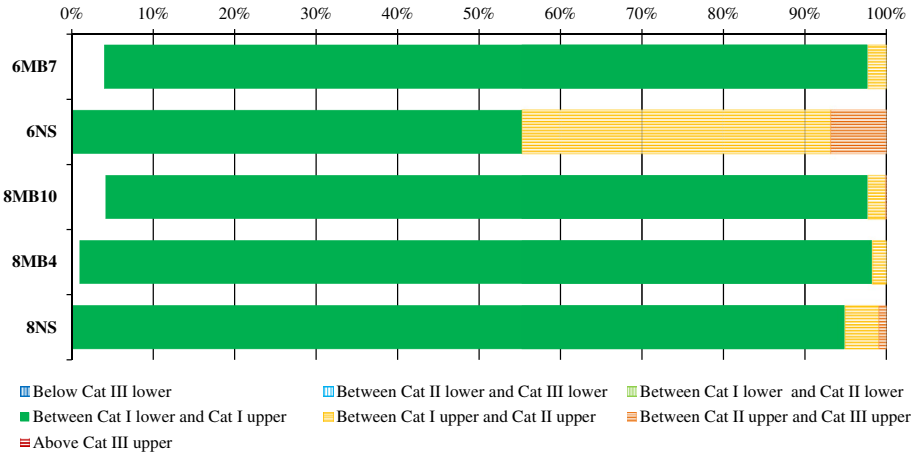


Fig. 8. Percentage time that measured internal temperatures lie within various BSEN15251 thermal comfort categories.

noted above, may in fact be advantageous. Temperature deviations rarely stray beyond the Cat II limit even at night, and are thus conditions that ought to be comfortable for nursing staff and visitors.

The measured temperatures in all the monitored spaces are compared using the bar chart approach recommended in BSEN15251 (Fig. 8). The nursing stations are included as a point of comparison although as interior spaces that are mechanically ventilated with no operable windows they are not strictly covered by BSEN15251. It is evident that for the most part all the spaces fall within the limits, there are occasional periods with low temperatures, which are mainly at night.

The key point to be made from these measured results is that, through a combination of occupant and facilities management control, ward temperatures are controlled in a manner consistent with an adaptive model of thermal comfort. This suggests that the adaptive model may well be applicable to hospital wards. Further monitoring on the DeDeRHECC project will provide further evidence.

7. Modelling and calibration

To predict the future likely conditions in the hospital a dynamic thermal model had to be created but to ensure that it predicted reasonably well the actual conditions in the wards, it was calibrated so that the predicted temperatures matched the measured temperatures. It isn't possible with a large building like a hospital to model, calibrate, predict and then interpret results for all the spaces, and the overwhelming amount of data might not improve generic understanding of the climate resilience of hospital wards.[27] Large models can also limit the number of simulations possible as even modest retrofit proposals could mean changes to many parameters. This paper therefore focuses on just one space; the south east facing seven bed ward, 6MB7 (Fig. 3).

The ward was modelled using the IES dynamic thermal simulation software [42] and the weather data for 2010 (see above) was used to drive the model. The room was 70.3 m^2, volume 190 m^3, 2.7 m from floor to ceiling with a 0.9 m deep space above (floor to floor height 3.9 m), the window area was 10.4 m^2 (transparent glazing, see above for U-values etc). The radiant ceiling set point was 30 °C in summer and 32.5 °C in winter and the ventilation supply air set point 18 °C, as advised by the facilities managers (see above). Internal heat gains from the lighting, bed-side lamp, TV etc, were small and set at 6.7 W/m^2. Other aspects of the heating and ventilation systems were known only roughly, most importantly the mechanical ventilation rate (set at 4ach^{-1}), the occupant's use of the operable windows and the air flow between the room and the above-ceiling void; the predicted room temperatures were very sensitive to assumptions about these three parameters.[28] Other parameters are also uncertain, not least the infiltration rate, and as is normal when modelling, many thermal factors were ignored, such as heat bridging and inter-zonal heat exchange (surrounding spaces were assumed to be the same as the modelled space and doors closed). The adjustments to the three most sensitive input parameters, to produce a reasonable match between measured and modelled room temperatures, is, therefore, also compensating for the uncertainty in many other features. Also, of course, actual performance is highly influenced by the interventions of facilities managers (e.g. in response to occupant complaints) and these cannot be reliably captured in a model. Further, the year 2010 prediction is based on Bedford weather, the micro climatic difference between Addenbrooke's hospital and Bedford weather station should be kept in mind when comparing measured and predicted results.

The final model is, of course, just one of a number that might be generated and with extended exploration the multi-dimensional space of possibilities could be fully explored. Nevertheless, the calibrated model performed reasonable well when the predicted temperatures were compared to the measured values (Fig. 9). Even so, it proved rather difficult to devise calibration values which would produce predictions similar to those measured for both the lower and upper BSEN15251 boundaries. Therefore priority was given to predicting HTM03 exceedences. The final model predicted that there would be 12 h above the HTM03 threshold between 1st July and 15th August, and there were actually 6 measured hours (see Table 1).

[27] The graphical interfaces to modern programs enable huge models to be built. Whilst necessary for testing compliance with regulations, for example generating building asset ratings, they can be unwieldy to adjust and it can be time consuming to set the control regimes (for example occupant window opening strategy) for the many spaces. Big models require users to make many assumptions and so it is debatable whether the insights gained are any better than those obtained from a single 'typical space' model that is adjusted in separate simulations to explore matters of importance – such as thermal mass, shading, passive ventilation rates etc.

[28] Occupants were assumed to open the windows if the wind speed was below 7.5 m^2. The maximum opening was 100 mm. The openings area was assumed to be 0% if $T_a \leq 15$ °C ramping up to 100% at 20 °C $\leq T_a \leq$ 21 °C, then closing to 25% at $T_a \geq 23$ °C. The air change rate between the room and void above the radiant ceiling was set at 2.5ach^{-1} and the background infiltration rate at 0.25ach^{-1}.

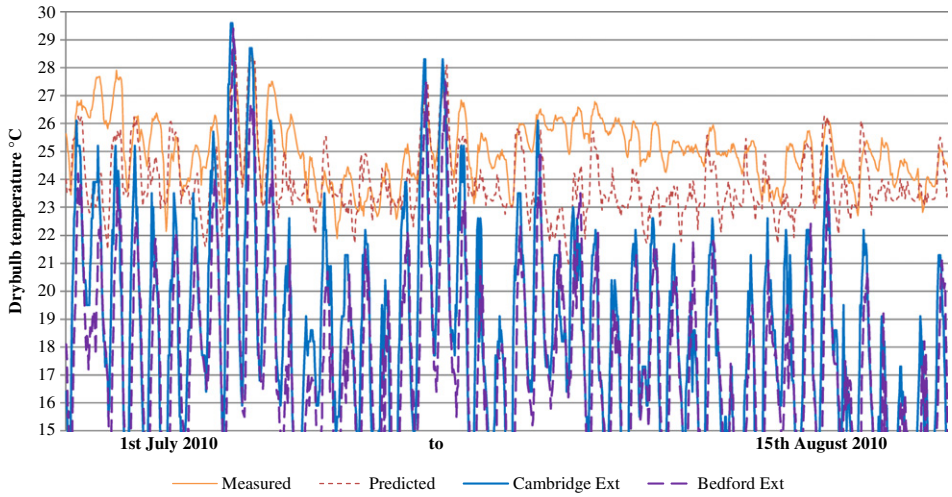


Fig. 9. Comparison of predicted and measured temperatures, and ambient temperature, during the monitoring period.

In all the simulations undertaken with the calibrated model, no changes were made to the control regimes for ventilation, heating and cooling. In practice of course, occupants would respond to short term thermal discomfort and adjustments to the control regimens would certainly be made by facilities managers to try and tune performance in the light of year-on-year changes in the climate; as they do at present to accommodate annual ambient temperature cycles. The model will though show the resilience to changing climate of the current ward with its existing energy systems and control settings. The impact of fans can be seen without the confusion that changing control strategies would introduce.

It is worth noting here that this 'calibration' process, as imperfect as it is, does at least produce a plausible model and one focussed on reliable overheating prediction, which is the nub of this paper. Very often predictions are made to assess retrofit options, but very rarely is any form of reconciliation against the known performance of the parent building attempted.[29]

8. Predicted current and future typical and extreme years internal temperatures

Using the calibrated model, predictions were made using both the TRY and the DSY for 2005 and the 2030s, 2050s and 2080s. The simulations were actually undertaken for the summer period, May to September, for which the simulated window control strategy was relevant. Control of overheating outside this time is relatively straight forward[30] and was assumed to be possible. Thus the assessment of overheating was made for a whole year enabling the HTM03 criterion, which is only applicable to whole years, could be applied. The statistics of predicted internal temperature, the number of hours for which the temperature exceed the HTM03 criterion of 28 °C and the CIBSE nighttime criterion of 26 °C, and the hours for which the BSEN15251 upper Cat I and Cat II thresholds were exceeded, are shown in Table 3 (upper block). The entries that exceed the threshold values are indicated.

It can be seen that by around the 2030s, in a typical year, the space would begin to overheat, but only marginally so, as judged by either the HTM03 criterion or BSEN15251 CatI threshold. In extreme years the space would be deemed uncomfortable by either method, even today. The nighttime temperatures follow the same pattern, marginally exceeding the CIBSE criterion in typical years by the 2030s and in extreme years even today. Interestingly, the space would be deemed comfortable in both typical and extreme years right up to the 2080s using the less stringent BSEN15251 Cat II threshold. This suggests, perhaps not surprisingly, that improving the thermal resilience of UK hospitals that are susceptible to climate change should focus on the patient areas, rather than the spaces with 'normal' occupants.

The frequency of overheating as judged by the HTM03 criterion increases markedly as the years warm (Fig. 10); in fact, roughly linearly with the increasing ambient temperature.[31] Thus in extreme years, which get much hotter in the future (Table 2), the overheating is extreme. However, the increase in overheating hours is much less marked when using the BSEN15251 Cat I or Cat II thresholds, particularly for typical years. This is because the standard accounts for the adaptation of individuals and their preference for warmer indoor temperatures in a warmer climate. Even so, because the extreme years become very much more extreme as the years pass, adaptation doesn't keep pace and the frequency of overheating increases even when an adaptive model is used (Fig. 10).

It is evident from this simple study, that unless the internal OT is maintained, either by active of passive systems, below the ambient temperature, or some other measure that affects thermal comfort, like the use of fans, overheating criteria, even those that account for adaptation, will probably not be satisfied in hot years in the relatively near future. Criteria based on internal dry-bulb temperature, like that in HTM03 will be much more difficult to satisfy and the retrofit options possible much more limited.

9. The effect of a simple retrofit measure

The DeDeRHECC team have an interest in the potential of fans for ameliorating the higher temperatures that climatic warming will bring. In fact, fans are often mentioned in NHS heatwave advice

[29] Calibration is rarely attempted in commercial modelling work, even when undertaken to evaluate refurbishment options; a period of simultaneous weather data and internal temperature, and possibly energy demand data, collection is just too expensive and time consuming to permit such an approach.

[30] As noted above, the manner of creating the TRYs and DSYs makes analysis of part years, made of whole months, quite acceptable.

[31] Seen for example by plotting the indoor hours above 28 °C against the ambient hours over this 28 °C.

Table 3
Summary of predicted internal temperatures, current (2005) and future Cambridge climate.

Years	Max. temp. (°C)	Min. temp. (°C)	Mean night time temp. (°C)	HTM03: Total hours over 28°C	CIBSE: Night time hours over 26°C	BSEN15251: Total hours above Cat I Upper limit	BSEN15251: Total hours above Cat II Upper limit	Max. temp. (°C)	Min. temp. (°C)	Mean night time temp. (°C)	HTM03: Total hours over 28°C	CIBSE: Night time hours over 26°C	BSEN15251: Total hours above Cat I Upper limit	BSEN15251: Total hours above Cat II Upper limit
TRY, no fan								**DSY, no fan**						
2005	28.6	21.3	24.2	10	10	1041	399	30.1	21.3	24.3	115	60	1198	497
2030s	30.6	21.6	24.3	93	59	859	395	33.0	21.2	24.7	383	231	711	341
2050s	31.0	21.2	24.3	163	87	866	351	34.8	21.8	25.2	620	388	938	445
2080s	31.7	20.7	24.5	232	152	695	285	36.5	20.9	26.0	1035	609	1132	645
TRY, -1.2°C fan cooling								**DSY, -1.2°C fan cooling**						
2005	27.4	21.3	24.2	*na*	1	791	201	28.9	21.3	24.3	*na*	27	888	180
2030s	29.4	21.6	24.2	*na*	15	447	72	31.8	21.2	24.5	*na*	102	332	86
2050s	29.8	21.2	24.3	*na*	26	405	61	33.6	21.8	24.9	*na*	210	391	124
2080s	30.5	20.7	24.4	*na*	62	295	71	35.3	20.9	25.5	*na*	413	581	326
TRY, -2.0°C fan cooling								**DSY, -2.0°C fan cooling**						
2005	26.6	21.3	24.2	*na*	0	664	136	28.1	21.3	24.3	*na*	13	693	113
2030s	28.6	21.6	24.2	*na*	5	235	32	31.0	21.2	24.4	*na*	49	154	27
2050s	29.0	21.2	24.2	*na*	6	200	24	32.8	21.8	24.7	*na*	136	170	75
2080s	29.7	20.7	24.3	*na*	31	140	19	34.5	20.9	25.2	*na*	323	376	192

2030s, 200s and 2080s climate as created by the UKCP09 weather generator.

Night-time hours are 21:00 to 06:00.

Simulated hours are for May to September (153 days, 3672 hours).

The HTM03 threshold is based on dry-bulb temperature and rest are based on operative temperature.

The darker grey indicates where the exceedence is substantial and deemed important in that it could not be easily corrected by refining the simulated window control strategy. Light grey shows minor exceedance which might be rectified by refined control.

It is assumed that during the winter half of the year (October to April) the space will not overheat due to elevated ambient temperatures and solar gains. The limiting overheating values are therefore: HTM03, >50hrs over 28°C; BSEN15251, >438 hours above category upper thresholds and CIBSE, >37 night time hours (1%) over 26°C).

Small *italics* shows standard (HTM03) not applicable to fans.

as a way of improving thermal comfort during heatwaves. They could be installed in existing hospitals with minimal disruption, at low-cost and with small energy demand implications (fans might be rated at 40–70 W). Ceiling fans in particular introduce little noise, an important factor in hospitals. Concerns might centre around infection control and the hard-to-access surfaces of fan blades, safety given the moving parts, vandalism and the added maintenance associated with having potentially hundreds of fans across a hospital campus; but repair is easy and low-cost.

The value of fans to enhance air movement and improve thermal comfort in warm spaces (over an OT of 25 °C) is noted in the CIBSE Guide [25], which offers the observation that fans might be equivalent to reducing the spaces temperature by about 2 K. The use of fans has been taken seriously in the USA and, following work by [43], the ASHRAE Standard 55 [29] explicitly accounts for their effects on the effective temperature 'perceived' by occupants.[32] The standard considers both occupant controlled fans and automatic fans, and both are permitted for comfort control at higher ambient temperatures, i.e. above an OT of 25.5 °C. For fans without occupant

[32] Formally the standard effective temperature (SET) – the temperature of an imaginary space with very low air movement at which occupants' skin heat loss is the same as that under the actual temperatures and air speed (and humidity).

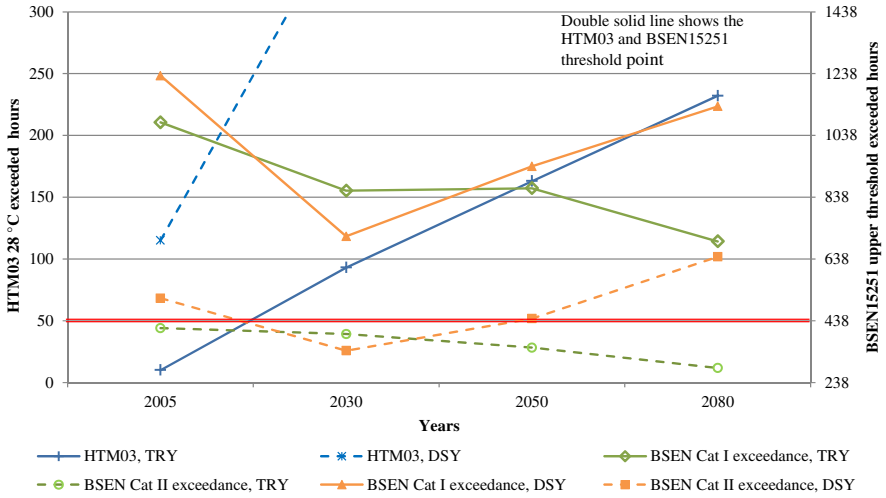


Fig. 10. Increase in overheating hours with changing climate as predicted by the HTM03 and BSEN15251 criteria.

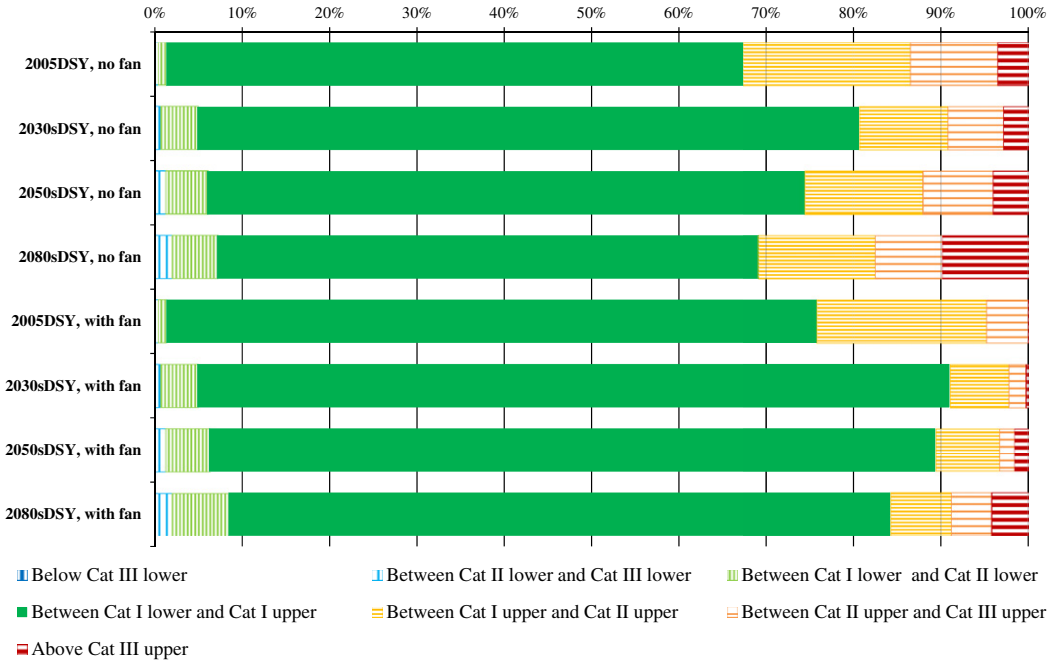


Fig. 11. Percentage time that predicted internal operative temperatures lie within various BSEN15251 thermal comfort categories in extreme years for Cambridge, 2005 to 2080s.

control the maximum permitted air speed above this temperature is 0.8 m/s [29]. The thermal comfort impacts of the two fan types is the same, but at some internal temperatures automatic fans might induce thermal discomfort in some people. The standard indicates that the impact of fans increases with air speed; 0.5 m/s being equivalent to an air temperature reduction of about 2 K.[33]

Importantly, the BSEN15251 standard also explicitly refers to fans as a useful mechanism by which occupants can adjust their thermal state in warm conditions. Within the standard, the cooling effect of fans is accounted for by increasing the upper bound of the thermal comfort envelopes when the fan is on. The increase depends on the speed of the air, following a very similar relationship to that in the ASHRAE standard. At a speed of 0.6 m/s the upper threshold of the comfort envelope is raised by 2 K, the maximum allowable air speed is 0.8 m/s. BSEN15251 suggest that adjustments to account for occupant controlled fans is valid under 'summer comfort conditions' at an indoor OT over 25 °C.

The analysis presented here was be done by simply post-processing the existing simulation results. Two air speeds were assumed 0.3 m/s and 0.6 m/s, which enable the OT to increase by 1.2 K and 2 K respectively. It was assumed that the fan was activated in the space when the OT in the room exceeded 26 °C. When modelling, it is a moot point whether this is achieved through occupant control or otherwise. In a hospital environment, there may be benefit in having manually operated fans in some spaces and in others automatic fans with simple temperature-related speed control and manual on/off override.

[33] The practical range of air movement is from 0.1 m/s (essentially still) to 0.8 m/s (which disturbs items in the room).

The results (Table 3) show that a fan, even one that generates modest air speeds, enables the ward to remain comfortable as judged by BSEN15251, right up to around the 2080s even in extreme years. Bar plots, following the style suggested by BSEN15251, show the percentage of the time that the ward is within the various category limits (Fig. 11). These indicate that there are times when the temperatures are below the lower limit of Cat I (but not Cat II); this would in practice be eradicated by occupants by turning off the fan or closing windows.[34]

The results suggest that fans could be very effective for mitigating the effects of climate change. However, the measurements and theory that describes their impact is largely underpinned by work based on normal healthy adults and office-type environments. Further work, including field studies, is needed before fans would become an accepted approach for climate change mitigation in UK hospitals. The analysis here justifies embarking on such work.

10. Conclusions and observations

The monitoring undertaken, albeit limited, indicated that the summertime conditions in three free-running hospital wards were regulated primarily by operable windows, and that the achieved temperatures conformed to the adaptive model of thermal comfort. That is, internal temperatures drifted with the ambient temperature, being generally higher at higher ambient temperatures.

The measured daytime temperatures in the three wards were, on all but a few occasions, within the BSEN15251 adaptive thermal comfort envelope applicable to sensitive and fragile persons with special requirements (Cat I). For all but 1 h the measured temperatures were within the Cat II envelope applicable to normal occupants.

In the nursing stations, where there was no provision for occupant control, the internal temperatures were high, leading to occupant dissatisfaction. The uncontrolled escape of heat from the improperly insulated radiant ceiling and from hot water pipes probably contributed to the overheating. Dissatisfaction was heightened because occupants had no mechanism for controlling the local temperatures: there are no operable windows and the thermostats associated with the radiant ceiling are in a poor state of repair.

The uncontrolled introduction of heat into buildings increases their susceptibility to overheating, especially when ambient temperatures are high, be that in warm spells, such as heat waves, or due to general climatic warming. Good practice in the maintenance and repair of existing energy services thus has an important role to play in improving the resilience of the existing NHS stock. The cost of doing this is relatively low and doesn't interfere with the functioning of the hospital. Indeed, diligent maintenance can also reduce energy wastage operating costs and CO_2 emissions.

Healthcare Technical Memorandum HTM03 indicates that indoor dry-bulb temperatures should not exceed 28 °C for more than 50 h a year. The use of dry-bulb temperature rather than operative temperature is unusual for contemporary thermal comfort guidelines. It inhibits the effective use of systems that rely on either passive of active radiant cooling, which is a useful way to enhance thermal resilience at relatively low-energy demand.

HTM03 makes no provision for the use of fans as an aid to improving thermal comfort, indeed, the use of dry-bulb rather than operative temperature inherently curtails a consistent approach to accounting for air movement. Fans are a low-energy, low-cost and low intervention approach to improving the thermal resilience of buildings.

As with all simple, static, overheating criteria, HTM03 cannot reasonably be used to assess the thermal comfort implications of future climate change in spaces that are free-running and controlled by the occupants, e.g. through operable windows. This is because the adaptation of people to the higher ambient temperatures is not accounted for. In general, the use of fixed-temperature criteria to assess free-running buildings seems increasingly inappropriate as we move into times with a more volatile and warming climate.

In contrast to HTM03, BSEN15251 is an adaptive thermal comfort standard based on limiting the deviation of operative temperatures outside a defined envelope. It explicitly enables both the measured and predicted performance in free-running buildings to be considered in a consistent way and is thus equally applicable to assessing performance in use and prediction for evaluating new builds or refurbishments. Credible analysis of the building's thermal resilience is possible and the amelioration of thermal discomfort by all forms of cooling (radiant, through air movement or by humidity control) can be assessed.

BSEN15251also offers different thermal comfort envelopes for different occupant types, Cat I for sensitive and fragile persons, and Cat II for normal occupants. This opens up the prospect of a lower standard of temperature control in some areas and tighter control in others, which will enable lower-cost, simpler and more robust building services provision in some less critical spaces. The standard enables those that commission, own and operate buildings to define the maximum allowable deviation from the standard's thermal comfort envelopes.

A dynamic thermal model was calibrated by comparing measured and predicted temperatures. It proved difficult to tuning the model to match the measured exceedences of both the upper and lower bound BSEN15251 envelopes. This is because occupant's influence on the temperatures in free-running buildings is difficult to replicate.

Predictions using the calibrated model, showed that a particular ward would be comfortable, but only marginally so, in typical years right though to the 2080s, as judged on a whole year basis using the BSEN15251 Cat I envelope. In extreme, 90 percentile hot years, the space was deemed uncomfortable even in the climate of today. Cat II spaces would be deemed comfortable even in extreme years right up to the 2080s.

Fans could enabled the ward to be comfortable right up to the 2080s even in extreme years, as judged on a whole year basis by the BSEN15251 Cat I envelope. They thus appear to be a rather simple and low-cost retrofit option for improving the thermal resilience of existing spaces.

In UK hospitals there is a move to the provision of single-bed wards. This opens up opportunities to provide occupants with personal control over their thermal environment. This prospect should be examined seriously, along with the many other benefits of single-bed wards, as it could improve the thermal comfort of occupants, improve hospitals' resilience to climate change and, by good design, improve energy efficiency and thus mitigate climate change.

An earlier paper [10] argued that an adaptive approach to thermal comfort should be considered for naturally ventilated healthcare spaces. This work has extended the argument to hybrid spaces and begun to support the assertion with physical measurement.

As the DeDeRHECC project proceeds, additional measurements from many other spaces, in different UK locations, will enable the applicability of adaptive thermal comfort standards to other hospital spaces be examined in more depth. The internal temperatures in these may, or may not, be controlled to within the BSEN15251 envelope. The likely future performance of other types

[34] Although not shown here, the possibility of including an allowance for fans within HTM03, by permitting a relaxation of the 28 °C criterion to 30 °C in spaces with fans was also examined. With such a relaxation the ward was predicted to remain comfortable in an extreme year to c2050.

of spaces will be tested and the added resilience afforded by different refurbishment methods will be assessed. The areas of the country in which mechanical is the necessary climatic adaptation solution will become clearer.

It is hoped that this paper will provoke debate about current thermal comfort standards and their appropriateness for assessing climate change adaptation and mitigation of buildings. The methodology use, which combines measurement and modelling, should be useful for assessing overheating risk in other building types.

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