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Adaptive Comfort Degree-Days: a metric to compare adaptive comfort standards and estimate changes in energy consumption for future UK climates

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Abstract
This paper introduces the concept of the Adaptive Comfort Degree-Day, a temperature difference/time composite metric, as a means of comparing energy savings from Adaptive Comfort Model standards by quantifying the extent to which the temperature limits of the thermal comfort zone of the Predicted Mean Vote Model can be broadened. The Adaptive Comfort Degree-Day has been applied to a series of climates projected for different locations (Edinburgh, Manchester and London) under different emissions scenarios in the United Kingdom for the 2020s, 2030s, 2050s and 2080s. The rate at which energy savings can be achieved by the European adaptive standard EN15251 (Category II) was compared with the ASHRAE 55 adaptive standard (80% acceptability) during the cooling season. Results indicate that the wider applicability of the European standard means that it can realise levels of energy savings which its counterpart ASHRAE adaptive standard would not achieve for decades.

Keywords
Adaptive Comfort Degree-Day (ACDD), Adaptive Comfort Model; UK Climate Projections 2009 (UKCP09); thermal comfort

1 Introduction
Temperatures over all parts of the United Kingdom are forecast to rise over the course of the next century as a consequence of climate change. The implications for energy consumption across the built environment are, however, less clear. Whilst elevated temperatures in the summer could result in an increase in the amount of energy used for cooling if overheating is to be avoided, buildings may require less heating in winter. Should the installation of mechanical cooling systems become the de rigueur response to elevated summer temperatures, this raises the interesting possibility that the additional expenditure of energy on cooling in summer may outweigh energy savings made in winter. The Adaptive Comfort Model (ACM) has been proposed as providing designers and facilities managers with the opportunity of reducing energy consumption yet ensure that thermal comfort is maintained by allowing buildings to operate in free-running mode rather than use mechanical systems for cooling and/or heating. This arises as a consequence of the fact whilst mechanical systems require energy for their operation, buildings in free-running mode, where occupants can freely adapt their local/personal environment by opening/closing windows, altering dress etc, largely do not. Whilst buildings which use mechanical cooling or heating systems customarily use broadly fixed temperature limits which are independent of outdoor air temperature to define the upper and lower boundaries of the zone of thermal comfort[1], the fluid temperature limits of the ACM are set in relation to the variant outside air temperature [1; 2]. As outdoor air temperatures increase over the forthcoming decades, it is clear that a building which is reliant upon the PMV Model to maintain thermal comfort in summer will require more cooling energy the more often that a mechanical cooling system is called upon to prevent internal temperatures exceeding the fixed upper limit. Conversely, it can also be said that the ACM would realise this same level of increasing energy savings if the same building could otherwise be comfortably operated in free-running mode. In similar vein, the level of energy savings that could be achieved by the ACM in

[1] The Predicted Mean Vote (PMV) Model, as set out in BS EN ISO 7730:2005 [1], is the standard typically used to define these limits.

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winter by comfortably operating the building in free-running mode can be calculated as the amount of energy which would otherwise be consumed by the mechanical heating system it displaced.

However, although the equations of the ACM provide some degree of insight on potential energy savings, they cannot quantify such savings. This paper proposes a metric, the *Adaptive Comfort Degree-Day (ACDD)*, to quantify energy savings accruing from the adoption of a given ACM against the adoption of the PMV standard. Such a metric is likely to be of use to both facilities managers and, more widely, policy makers who wish to promote passive design strategies for free-running buildings.

The ACDD is analogous to the long-established cooling/heating degree-day, the temperature difference/time composite used to quantify the amount of cooling/heating required to maintain comfort using a given outdoor temperature as its base temperature. The base temperatures used in calculating the number of ACDDs is, however, set so as to correspond with the upper and lower limits of the zone of thermal comfort of the PMV Model under typical conditions as detailed in table A.5 of BS EN ISO 7730:2005 [3]. As such, the number of ACDDs acts as a measure of the performance of the ACM, a temperature difference/time composite quantification of the extent to which the temperature limits of the PMV Model can be exceeded: the ACDD total is in proportion to the maximum potential cooling/heating energy savings which could be achieved by the ACM, being an homologue of the quantity of energy which would otherwise be consumed by the mechanical system it displaced.

After explaining the concept of the ACCD in Section 2 and validating its capacity to act as a metric for predicting climate/weather related energy savings in Section 3, the remaining sections investigate the potential energy savings arising from implementation of the two adaptive standard options applicable within the United Kingdom, viz (i) the ANSI (American National Standards Institute)/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) adaptive standard 55-2004[2] [1], and (ii) the European adaptive standard BS EN 15251:2007[3] [2] for future climates under different emissions scenarios[4] over the coming century.

It should be noted that it has been contended that the European and ASHRAE adaptive standards are not directly comparable [4]. Whilst it remains true that differences with regard to the methods used in formulating the two standards limit the degree of comparability between them, comparison is possible and, indeed, necessary, for that group of free-running buildings where a mechanical cooling system has not been installed and where occupants possess individual adaptive opportunity. Given that the two Adaptive standards both set out to deliver comfortable, zero energy thermal environments, it is important to report the differences between them since differences in the energy saving potential, as determined by the number of ACDDs returned, are necessarily bound to different levels of thermal comfort.

2 The Adaptive Comfort Degree-Day

Where there is no latent load, the degree-day concept is predicated on the notion that an energy balance is achieved in a building when the sum of the heat inputs equals the overall heat losses.

Heating: $Q_s + Q_i + Q_h = Q_{f+v}$............................*Equation 1*

Cooling: $Q_s + Q_i = Q_c + Q_{f+v}$............................*Equation 2*

where

Q_s = *solar gains*
Q_i = *internal gains from people, equipment and lights*

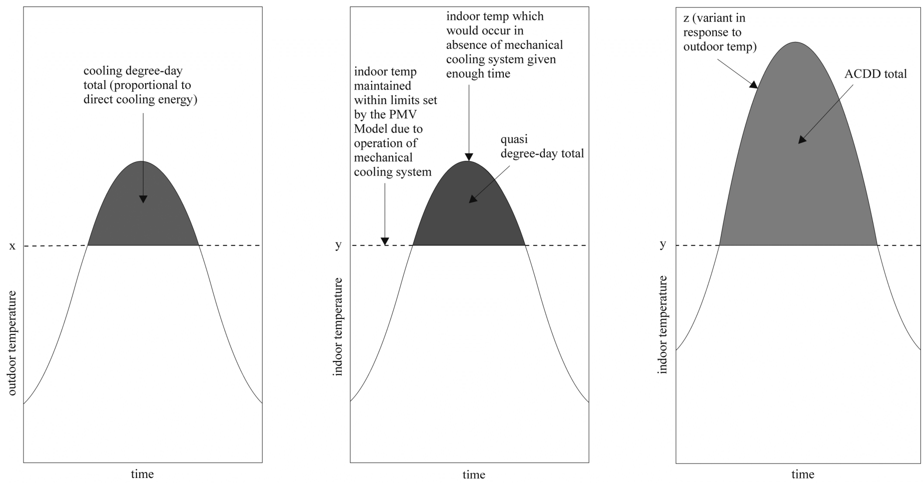
[2] Section 5.3 - The Optional Method for Determining Acceptable Thermal Conditions in Naturally Conditioned Spaces.
[3] Annex A.2 - Acceptable indoor temperatures for design of buildings without mechanical cooling systems.
[4] The emissions scenarios relate to emissions of substances that can affect the radiative balance of the globe (greenhouse gases (GHG), aerosols and their precursors).

Q_h = output from heating system
Q_c = output from cooling system
Q_{f+v} = heat flux from inside to outside (heat loss through building fabric + ventilation loss)[a]

where Q_{f+v} α Δt
where Δt = indoor-to-outdoor temperature difference
[a] heat/ventilation gains have a negative value

The underlying premise of the concept is that the incidental gains Q_s and Q_i, when averaged over a period of time, can be assumed to be constant, the consequence of which is that the demand for mechanical cooling/heating energy (Q_c or Q_h) is proportional to the heat flux from inside to outside (Q_{f+v}). As Q_{f+v} is proportional to the indoor-to-outdoor temperature difference (Δt), it is apparent that Q_c and Q_h are also proportional to Δt. In consequence, Δt can be seen to act as driving Q_c or Q_h (based on [5]). Since the summation of these temperature differences is equal to the number of degree-days for a given period of time, one can state that the demand for mechanical cooling/heating energy is proportional to the number of degree-days. Furthermore, a necessary adjunct of the concept, resulting from steady-state theory, is that, given enough time, the driving force applied by Δt would ultimately ensure that each degree rise in outdoor temperature would result in a rise in indoor temperature of equal magnitude in the situation where no mechanical system was in place to counteract the driver, Δt.

Taking cooling as an example, a cooling degree-day can be defined as the time integral of the mean daily outdoor air temperature above a particular base temperature (units: K.day). Where a building uses mechanical means to maintain thermal comfort and the base temperature is the outdoor trigger temperature (*x*) which calls the cooling system into operation (such temperature corresponding with an indoor temperature of *y*), it can be seen that the amount of cooling energy required is in proportion to both (i) the number of cooling degree-days (figure 1 (a)) and (ii) the number of quasi cooling degree-days (figure 1 (b)).



1(a) **1(b)** **1(c)**

Figure 1 Adaptive Comfort Degree-Day concept explained by analogy with the traditional cooling degree-day – (a) Cooling degree-day total as a function of outdoor temperature and time, (b) Quasi cooling degree-day total as a function of indoor temperature and time, (c) ACDD total as a function of indoor temperature and time

Similarly, the amount of heating energy required to maintain thermal comfort when the daily mean outdoor temperature drops below a specific trigger base temperature is proportional to the heating degree-day total or quasi heating degree-total.

The Adaptive Comfort Degree-Day functions in analogous fashion to the quasi degree-day, its value being in direct proportion to potential energy savings arising from use of the ACM in a building in place of the PMV Model. Taking cooling as an example again, whereas a building using the PMV Model must call upon an energy-consuming system once the indoor temperature of *y* is reached in order to prevent internal temperatures further rising above this limit, the ACM may allow temperatures to extend beyond this limit whilst still maintaining thermal comfort. In such a case, the upper temperature limit of the thermal comfort zone set by the ACM (*z*) varies in accord with the varying mean outdoor air temperature (figure 1(c)). By simple analogy with the quasi degree-day, the potential energy savings which can be achieved by supplanting the PMV Model with the ACM are in proportion to the magnitude of cooling energy which would otherwise be consumed by a mechanical system in maintaining an indoor temperature of *y* and preventing it from reaching an indoor temperature of *z*. By allowing the building to free-run rather than use a mechanical cooling system, the maximum potential energy savings can therefore be simply calculated as being proportional to the time integral of the varying *z* above the fixed base temperature of *y* (units: ACDD).

It should be remembered that the cooling ACDD is a direct correlate of the non-latent (ie chilling) component of the energy consumption of a mechanical cooling system. As such, whilst the potential energy savings for systems involving no transfer of heat by latent loads (eg chilled beams/ceiling cooling system) are in direct proportion to the number of ACDDs, the level of the potential energy savings for other mechanical systems involving latent loads (eg fan coil systems) will be even greater than the number of ACDDs. Whilst the example given here refers to cooling, the ACDD may equally well be used to estimate maximum potential heating energy savings where a building free-runs during the heating season rather than uses an energy-consuming heating system.

3 Validating the Concept of the ACDD

The concept of the ACDD is wholly reliant upon the assertion that, under steady-state conditions, each degree rise in outdoor temperature would result in a rise in indoor temperature of equal magnitude in the situation where no mechanical system were in place to counteract that indoor rise in temperature. Whilst it is clear that, given enough time, the indoor temperature in a building of heavyweight construction would eventually reach the same indoor temperature as that of a building of lightweight construction, there will be many situations where there is insufficient time for the equilibrium to be established On a hot summer day, the total heat flux from outside to inside through the fabric of a heavyweight building would be less than that through the fabric of a lightweight building, where a proportion of the heat *locked* in the thermal mass of the heavyweight building during the day would be re-transmitted back to the outside during the coolness of the night, without ever having reached the inside. In the non-steady state of the real world, on a hot summer day the indoor temperature inside a quickly responding lightweight building is always likely to be higher than that inside its slowly responding heavyweight counterpart in the absence of a mechanical cooling system.

Similarly, in the non-steady state of the real world, the indoor temperature inside a highly glazed building is always likely to be higher than that inside a building with a low level of glazing on a hot summer day in view of the different lengths of time each building would take to reach equilibrium. This is of particular importance since the ACDD relates energy savings to air temperature alone without taking into consideration the influence borne by solar radiation.

It is clear, therefore, that the ACDD concept must be tested under non-steady-state conditions using real weather data for buildings of (i) different construction types (and therefore different thermal responsivenesses) and (ii) different levels of glazing, before it can be used to forecast energy savings under a changing climate.

Sections 3.1 and 3.2 describe the method used to test for the existence of a correlation between actual cooling energy savings and calculated ACDD totals, and section 4 presents the correlation results.

3.1 Building Simulation

A range of simple, single storey buildings of dimensions 15m x 25m x 3.5m of different thermal responsivenesses was designed using the modelling software package, DesignBuilder. Five different construction types using five different levels of evenly-spaced glazing (10%, 30%, 50, 70% and 90% wall coverage) (table 1) were modelled. Thus a total of 25 buildings were used in the study.

Table 1 Construction of buildings used in energy simulations

LIGHTWEIGHT CONSTRUCTION, FLAT ROOF (LIGHT)
Walls (i) 6mm lightweight metallic coating, (ii) 88.9mm extruded polystyrene, (iii) 13mm gypsum plasterboard
Roof (i) 10mm asphalt, (ii) 144.5mm glass wool, (iii) 200mm air gap, (iv) 13mm plasterboard
Windows Double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

MEDIUM WEIGHT CONSTRUCTION, FLAT ROOF (MEDIUM)
Walls (i) 100mm brickwork outer leaf, (ii) 79.5mm extruded polystyrene, (iii) 100mm concrete block (medium), (iv) 13mm gypsum plastering
Roof (i) 10mm asphalt, (ii) 144.5mm glass wool, (iii) 200mm air gap, (iv) 13mm plasterboard
Windows double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

MEDIUM WEIGHT CONSTRUCTION, PITCHED ROOF WITH EAVES (PITCHED)
Walls (i) 100mm brickwork outer leaf, (ii) 79.5mm extruded polystyrene, (iii) 100mm concrete block (medium), (iv) 13mm gypsum plastering
Roof (i) 25mm clay tiling, (ii) 10/20mm air gap, (iii) 5mm roof felt
Ceiling (i) 10mm plywood (heavyweight), (ii) 139.1mm glass wool, (iii) 100mm cast concrete (lightweight), (iv) 13mm plasterboard

HEAVYWEIGHT CONSTRUCTION-HIGHLY INSULATED, FLAT ROOF (HEAVY)
Walls (i) 105mm brickwork outer leaf, (ii) 118.2mm extruded polystyrene, (iii) 100mm concrete block (medium), (iv) 13mm gypsum plastering
Roof (i) 10mm asphalt, (ii) 251.2mm glass wool, (iii) 200mm air gap, (iv) 13mm plasterboard
Windows double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

SOLID WALL CONSTRUCTION, SOLID FLAT ROOF (SOLID)
Walls (i) 20mm external render, (ii) 50mm phenolic foam (foil-faced), (iii) 225mm brick, (iv) 13mm dense plaster
Roof (i) 19mm asphalt, (ii) 13mm fibreboard, (iii) 204.7mm extruded polystyrene , (iv) 100mm cast concrete (lightweight)
Windows double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

The design incorporated a fan-coil air-conditioning system with a set point of 26ºC (operative temperature). The total cooling energy (including the latent component) under typical patterns of office occupancy (unoccupied during the night and at weekends), equipment gains, metabolic activity, clothing, lighting and air-tightness for a generic office area was modelled using EnergyPlus software made available by the US Department of Energy. The simulations were carried out at time-steps of 10/hour for a total of 22 locations (table 2) using International Weather for Energy Calculations (IWEC) weather data. Derived from up to 18 years (1982-1999) of hourly weather data observations, and supplemented by solar radiation data estimated on an hourly basis from earth-sun geometry and hourly weather elements, (particularly cloud amount information), the weather data constitutes weather conditions typical for the specific location [6], being the ASHRAE equivalent of the Test Reference Years (TRYs) produced by the Chartered Institution of Building Services Engineers (CIBSE). The construction types, levels of glazing and locations used were specifically chosen to present a broad cross-section of the building stock in terms of cooling requirements ranging from Oban in the west of Scotland to Marseille in the south[5]; taking a medium weight building with a flat roof and 30% glazing as a typical example, the building in Marseille consumes almost 27 times as much energy for cooling as the building in Oban (table 2).

Table 2 Electricity consumed by a MEDIUM building with 30% glazing in chilling the air to a set point operative temperature of 26ºC for 22 locations – solar data and air temperature data also shown

Location	Summer Mean (Jun-Aug) Dry Bulb Temp (ºC)	Annual Mean Dry Bulb Temp (ºC)	Total Cooling Energy Consumption (kWh)	Solar Gains - Window (kWh)	Direct Normal (kWh/m^2)	Diffuse Horizontal (kWh/m^2)
Aberdeen	13.3	8.3	732	21568	483	616
Oban	13.5	9.2	661	21209	588	547
Aughton	14.7	9.5	881	22376	600	605
Hemsby	15.3	9.8	1709	24411	690	641
Finningley	15.6	11.2	2011	22622	597	622
Brest	15.6	11.2	2229	24570	661	688
Birmingham	15.9	9.6	2264	24184	627	670
Jersey	16.2	11.2	2992	26499	891	633
Gatwick	16.3	10.1	3296	23803	743	593
Cologne	17.1	9.9	4428	22503	564	648
Brussels	17.1	10.3	4116	21352	509	630
Nancy	17.8	10.1	6064	24637	729	657
Frankfurt	18.2	10.1	5698	23866	723	615
Nantes	18.4	12.2	7073	27090	885	665
Paris	18.6	11.2	6382	24282	679	669
Dijon	19.1	10.7	7590	26257	812	682
Mannheim	19.2	11.1	7620	24255	727	638
Bordeaux	20.2	13.3	9672	28631	930	712
Odessa	21.1	9.9	10184	26659	831	701
Turin	21.5	12.4	14927	28648	1035	653
Montpellier	22.7	14.9	15889	32531	1320	666
Marseille	23.3	15.0	17815	33737	1504	615

3.2 Cooling ACDD Calculation

The upper temperature limits defining the zones of thermal comfort were calculated for each location for each adaptive standard as outlined in Table 3, the daily mean outdoor temperature being taken as the average of the daily maximum and daily minimum temperatures.

Table 3 Operative temperature limits of comfort zone (ºC)

ASHRAE 55 adaptive standard[b]	
upper limit	$0.31 \times t_{mm} + 17.8 + x$
lower limit	$0.31 \times t_{mm} + 17.8 - x$
	t_{mm} = *mean monthly outdoor air temperature*
European 15251 adaptive standard	
upper limit	$0.33 \times t_{rm} + 18.8 + y$
lower limit	$0.33 \times t_{rm} + 18.8 - y$

[5] All seven of the IWEC locations on mainland United Kingdom (plus Jersey) were used in the analysis. Marseille was chosen as its ACDD totals/summer temperature (23.2ºC) approximates those forecast for London under a high emissions scenario for the 2080s (22.7ºC at the 0.5 probability level). The remaining 13 European locations, primarily from western Europe, were chosen so as to ensure a good range of ACDD totals/temperatures. The results of all analyses are shown in Section 4 – no data were omitted.

t_{rm} = daily running mean outdoor air temperature

where x = 2.5 or 3.5   y = 2, 3 or 4

[b] *Note that the ASHRAE adaptive standard equations are not contained within the standard itself but can be found in other documents produced by the authors such as [7] and [8].*

3.2.1 Thermal Comfort Benchmarks

The necessity of comparing on a like-for-like basis is evident. As the ACMs and the PMV Model propose a number of different upper and lower temperature limits which allow for different levels of acceptable deviation from the neutral temperature (*x* and *y* in Table 3), the question arises as to which limits should be chosen for comparison when calculating the number of ACDDs.

PMV Model

The PMV Model [3] sets out three different comfort zones, Categories A, B and C, where PPD values can be used to delineate one category from another (table 4).

Table 4 Categories used to define the temperature limits defining the thermal comfort zones of the PMV Model as defined by BS EN ISO 7730:2007

Category	PPD values (%) – whole body discomfort	PMV
A	<6	-0.2 < PMV < +0.2
B	<10	-0.5 < PMV < +0.5
C	<15	-0.7 < PMV < +0.7

ASHRAE adaptive standard

The ASHRAE adaptive standard sets out two thermal comfort zones – one for 80% acceptability, and another for 90% acceptability. Since the 80% acceptability comfort zone used in ASHRAE standard 55 for buildings which employ mechanical cooling systems (and which uses the PMV Model) is based on a predicted percentage dissatisfied (PPD) value of 10 for general whole body thermal discomfort[6] [9], it is reasonable to attach this same value of PPD 10 for whole body thermal discomfort to the 80% acceptability limits of the ASHRAE adaptive standard.

European adaptive standard

BS EN 15251:2007 sets outs out both the adaptive standard for buildings without mechanical cooling systems and the PMV standard for buildings which employ a mechanical cooling and/or heating system. Whilst four different comfort zones are distinguished (table 5), only the first three zones (Categories I, II and III) are used by the adaptive standard.

Table 5 Categories used to define the temperature limits defining the thermal comfort zones in BS EN 15251:2007

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
II	Normal level of expectation and should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Categories I, II and III of BS EN 15251:2007 correspond with Categories A, B and C in BS EN ISO 7730:2005, (the same PMV values being used to delineate the categories).

[6] An allowance is made for an average of a further 10% dissatisfaction that might occur because of local thermal discomfort, in addition to the general whole body 10% dissatisfaction mentioned above.

Thus, as the PMV Model correlates to both (i) the ASHRAE adaptive standard (at the whole body PPD level), and to (ii) the European adaptive standard (at the category level), it can be seen that direct comparison can be made between the two adaptive standards. Since the 80% acceptability ASHRAE adaptive standard corresponds to the European adaptive standard Category II (the commonality being the PPD value of 10 for whole body discomfort), ACDDs for both adaptive standards were consequently calculated with reference to Category B of the reference PMV Model.

3.2.2 Application of Cooling ACDD Equations

The basic form of the equation used to calculate the number of cooling ACDDs for each location is described by equation 3.

$$ACDD_c = \sum_{i=1}^{12}(ACM_{ul}-PMV_{bs}) \quad \text{.............................Equation 3}$$

when $ACM_{ul} > PMV_{bs}$
where
$ACDD_c$ = *annual number of cooling ACDDs*
ACM_{ul} = *ACM upper temperature limit*
PMV_{bs} = *PMV base temperature for cooling season*

In similar vein to conventional degree-days, ACDD values calculated as having a negative value assume an actual value of 0, since the ACDD metric is only a measure of the extent by which the ACM_{ul} exceeds the PMV_{bs}

Henceforth, the ASHRAE 55 adaptive standard (80% acceptability) is termed the AAS and the European 15251 adaptive standard (Category II) is termed the EAS for brevity.

In view of the fact that both the AAS and the EAS only apply to spaces where the occupants are engaged in near sedentary physical activities with metabolic rates ranging from 1.0 to 1.3 met, comparison across all ACMs is limited to buildings such as offices, dwellings, schools and laboratories where the metabolic rate is of the order 1.2 met.

The resultant base temperatures so used as corresponding to the PMV/PPD values in table 4 and metabolic rate of 1.0-1.3 used in the calculation of ACDDs derive from the PMV Model as detailed in BS EN ISO 7730:2005[7] [3], the PMV base temperature for summer months (PMV_{bs}) being 26.0ºC[8].

Regarding the necessity that comparison be made on a like-for-like basis, it is re-iterated that the AAS/EAS comparison is only valid for those buildings in which a mechanical cooling system is not present. Even though the EAS can, in general, apply to buildings in which a mechanical cooling system has been installed given the proviso that the system is not actually used to provide cooling, the comparison only remains valid for that sub-section of buildings completely lacking a mechanical cooling system so as not to invalidate the applicability of the AAS.

The number of cooling ACDDs was calculated for each ACM thus:

AAS	$ACDD_c = \sum_{i=1}^{365} (ACM_{ul} - 26.0)$ ....*Equation 4* *when* $ACM_{ul} > 26$ *where* $ACM_{ul} = 0.31 \times t_{mm} + 17.8 + 3.5$

[7] The base temperatures refer to spaces under the typical conditions of air velocity, relative humidity, clothing insulation and metabolic activity as outlined in Annex A.4 of BS EN ISO 7730:2005 where the air temperature is equal to the operative temperature.
[8] The PMV base temperature for winter months (PMV_{bw}) is 20.0ºC.

EAS	$ACDD_c = \sum_{i=1}^{365} (ACM_{ul} - 26.0)$ ....Equation 5 *when* $ACM_{ul} > 26$ *where* $ACM_{ul} = 0.33 \times t_{rm} + 18.8 + 3$

Noteworthy of mention are the facts that the ASHRAE 55 adaptive standard (80% acceptability) is described as being intended for use in "typical applications" [1], and (ii) the European adaptive standard (Category II) is described as being intended for a "normal level of expectation and should be used for new buildings and renovations" [2]: inasmuch as these are the two principal adaptive standards proposed as bearing the greatest capacity to influence design, the present comparison is, therefore, considered to be not only valid on the grounds of equality in terms of PPD values, but also in terms of appropriacy.

The number of annual cooling ACDDs was calculated using the IWEC weather data for each of the 22 locations, and plotted against the total cooling energy consumption of the air-conditioning systems for each of the 25 building types.

4 Validation Results

The correlation between ACDDs and total cooling energy consumption shows a remarkable degree of consistency across the whole range of building types and for all locations, despite the fact that the cooling energy includes both the latent load in addition to the sensible load. (In humid climates where loads are high, one might expect to find a diminution in correlation due to increased latent loads.) Ranging from a minimum value of 0.89 for the PITCHED building with 10% glazing using the EAS, the coefficient of determination reaches a maximum of 0.99 for the PITCHED building with 50% glazing using the AAS and the SOLID building with 30% glazing using the EAS, as shown in figure 2 and table 6.

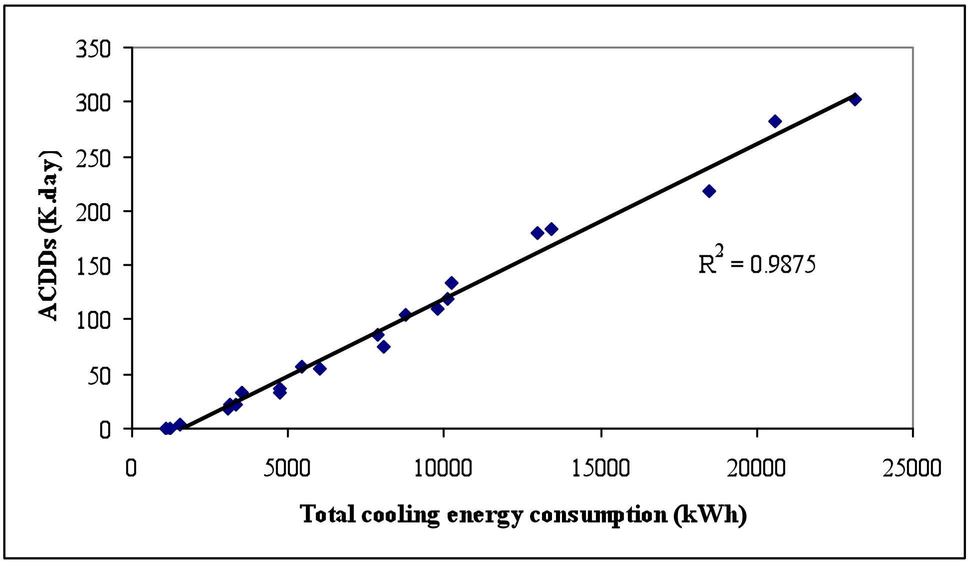


Figure 2 Correlation between annual number of cooling ACDDs using the e AAS and total annual cooling energy consumption for the PITCHED building with 50% glazing for 22 different locations

Table 6 Coefficients of determination for a range of construction types in the plot of annual number of cooling ACDDS against total annual cooling energy consumption

Level of glazing	LIGHT		MEDIUM		HEAVY		PITCHED		SOLID	
	AAS	EAS	AAS	EAS	AAS	EAS	AAS	EAS	AAS	EAS
10%	0.95	0.98	0.93	0.96	0.96	0.98	0.89	0.94	0.91	0.95
30%	0.98	0.98	0.97	0.98	0.98	0.98	0.96	0.98	0.97	0.99
50%	0.98	0.98	0.98	0.98	0.98	0.97	0.98	0.99	0.98	0.98
70%	0.98	0.97	0.98	0.97	0.97	0.97	0.98	0.98	0.98	0.98
90%	0.97	0.97	0.97	0.97	0.97	0.96	0.98	0.98	0.98	0.97
Mean	**0.97**	**0.98**	**0.97**	**0.97**	**0.97**	**0.97**	**0.96**	**0.98**	**0.96**	**0.97**

Although the coefficient of determination was very high for each of the 50 regression analyses carried out, it was noted that in two of the EAS analyses ((i) PITCHED, 10% glazing, and (ii) SOLID, 10% glazing) and one AAS analysis (PITCHED, 10% glazing), the correlation started to deteriorate if the demand for cooling was very low. Most clearly observed in the EAS PITCHED, 10% glazing regression (figure 3), the decline in the correlation can largely be ascribed to the fact that a zero cooling energy demand does not correlate with zero ACDDs. Essentially, the mismatch results from the fact that although the ACM would allow indoor temperatures to exceed 26ºC on occasion, actual temperatures within buildings with very low levels of glazing in certain of the colder climates would only exceed 26ºC on a low number of occasions if allowed to free-run. Whilst, for example, in neither Aughton nor Aberdeen would the PITCHED building require a mechanical cooling system to maintain a temperature below 26ºC, the upper limit of the ACM (reflecting the number of ACDDs) does, periodically, stretch beyond 26ºC in both towns.

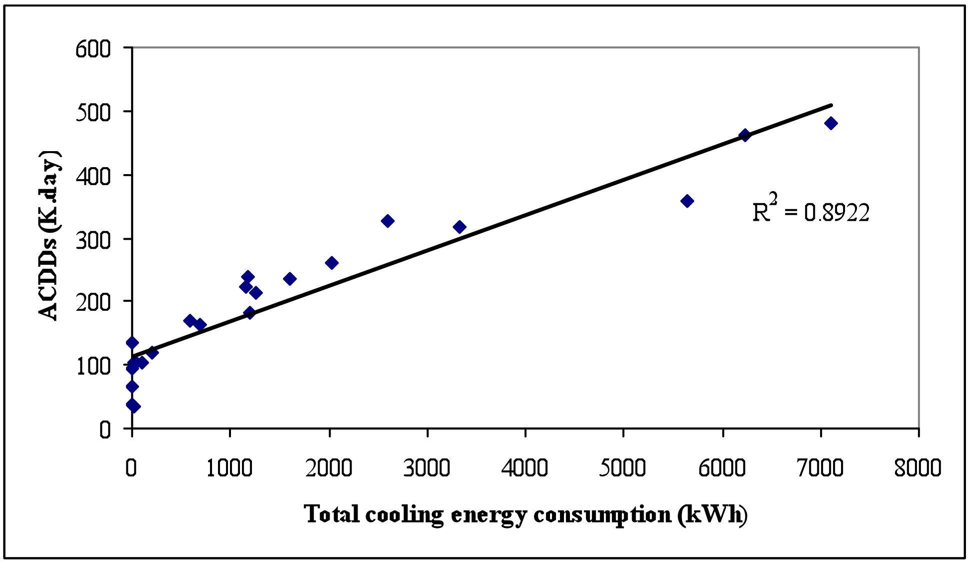


Figure 3 Correlation between annual number of cooling ACDDs using the EAS and total annual cooling energy consumption for the PITCHED building with 10% glazing for 22 different locations

Even though application of the ACM requires that there be access to openable windows, which may preclude its use in many of the more extreme construction types (eg 10% glazing and 90% glazing, such latter highly glazed buildings often likely to have been built so as to specifically incorporate an air-conditioning system and possessing sealed windows), the coefficient of determination across all construction types averages as 0.97 for both the AAS and the EAS.

4.1 Discussion of Validation Results

4.1.1 Thermal Responsiveness of Buildings

The fact that the correlation between cooling energy consumption and cooling ACDDs remains high for the whole range of construction types, irrespective of thermal responsiveness, indicates that the predictive capacity of the ACDD concept does not require attainment of the steady-state. The indoor temperature which would occur in the steady-state acts as no more than an alternative, convenient metric to measure the driving force of heat flux across the fabric of the building, where the greater the notional steady-state temperature, the greater the heat flux, such heat flux being equal and opposite to the applied cooling energy.

4.1.2 Solar Gains

The finding that the coefficients of determination are largely uniform across all levels of glazing is indicative of the relatively much lesser importance of solar radiation than outdoor air temperature (and therefore ACDDs) in affecting indoor temperature. High levels of direct normal solar radiation are not translated into high levels of solar gains: despite the large differences in the levels of direct normal solar radiation across the range of locations investigated (coefficient of variation – 31%), the coefficients of variation for solar gains show a much higher degree of uniformity, the coefficient of variation being of the order of 5 - 7% for the summer months during which the cooling load is at its greatest, and 12% over the full course of the year (table 7).

Table 7 Coefficients of variation for (i) solar radiation and (ii) solar gains through glazing for a range of construction types for 22 locations

	Coefficient of variation (Jan-Dec) (%)	Coefficient of variation (Jun-Aug) (%)
Direct Normal Solar Radiation (kWh/m^2)	31.4	31.3
Diffuse Horizontal Solar Radiation (kWh/m^2)	6.6	5.8
Glazing Solar Gains for a given level of fenestration (LIGHT, MEDIUM, HEAVY, SOLID) (kWh)	6.7	12.9
Glazing Solar Gains for a given level of fenestration (PITCHED) (kWh)	5.4 - 6.5[c]	12.4-12.7 [c]

[c] *The value of the coefficient of determination is dependent upon the degree of fenestration for PITCHED buildings as a consequence of the differential levels of shading provided by the eaves.*

Whilst, for example, Marseille receives over three times as much direct normal solar radiation than Aberdeen, this translates into additional solar gains of only 56% for the MEDIUM building (30% glazing) (table 2) since a large part of the additional Marseillaise sunshine occurs when the sun is high in the sky. This dominance of air temperature over solar gains in determining indoor temperature/cooling load can be seen in any number town-town comparisons in table 2: whereas the MEDIUM (30% glazing) building receives 36% more direct normal radiation in Hemsby than in Brussels, its cooling load is 58% less in consequence of the fact that air temperatures are considerably lower in Hemsby than in the Belgian capital.

Albeit that solar radiation is of lesser significance than air temperature, a further reason for the very good correspondence between the number of ACDDs and cooling energy consumption is that solar radiation is largely not antagonistic to this relationship, there being a similarly high correlation between the number of ACDDs and solar gains: the coefficient of determination falls in the range 0.78-0.81 for all building types and levels of glazing for both adaptive standards.

It is worth noting that although the validity of the ACDD concept rests on no greater assumption than that there is linear correlation between the notional steady-state indoor temperature and outdoor temperature in a passively cooled building, these results are in close accord with Coley and Kershaw's finding of the close relationship between actual indoor temperature and outdoor temperature; modelling a number of different passively cooled building types using (i) weather data projected for the UK and (ii) observed weather data from a very wide range of climates including the humid Tokyo and Bangkok as well as London, a near linear relationship between actual indoor temperature outdoor temperature was found [10].

Summarily, the regression analyses confirm the postulation that for (i) a given construction type, and (ii) a given level of glazing, cooling loads can be predicted by the difference between the outdoor temperature and the notional indoor steady-state temperature, the accuracy of the prediction being most accurate for buildings where the steady-state temperature more often exceeds 26ºC. The sequitur of this finding is that the ACCD can be used as a metric to forecast energy savings at different times in the future under a changing climate, thereby allowing one to compare the maximum potential savings deriving from the AAS and the EAS.

5 Forecasting the future climate

The UK Climate Projections 2009 (incorporating the UKCP09 Weather Generator) (UKCP09) give probabilistic projections for a number of atmospheric variables for several future time periods until the 2080s, under three future emissions scenarios [11]. Having undergone extensive review, the Climate Projections are the result of seven years of work by (i) the Met Office Hadley Centre, (ii) the UK Climate Impacts Programme (UKCIP) and (iii) a body of over thirty contributing organisations including the Climatic Research Unit, widely recognised as one of the world's leading institutions concerned with the study of natural and anthropogenic climate change [12; 13]. The Climate Projections derive from the Met Office Hadley Centre climate model HadCM3, one of the major models used in the Intergovernmental Panel on Climate Change (IPCC) Third and Fourth Assessment Reports [14], and also include the results of other IPCC climate models [15]. Differing from its predecessors in that it takes account of known sources of uncertainty and subsequently quantifies the degree of that uncertainty, UKCP09 reflects scientists' best understanding of how the climate system operates [16].

Since the modelling of future climate change requires estimation of future levels of emissions (such emissions levels being the product of complex dynamic systems, determined by factors such as changes in demographics, socio-economic development, and technological advances), UKCP09 employs a number of different scenarios to take account of these uncertainties [17]. The different emissions scenarios so used were developed by the IPCC in their Special Report on Emissions Scenarios (SRES) [18] - high (SRES A1FI), Medium (SRES A1B) and Low (SRES B1) – and were used in the IPCC Fourth Assessment Report.

As useful as the actual climate projections themselves are in allowing one to attach a probability to the occurrence of any given future climate, relative evaluation of the performances of the AAS and the EAS over the course of the century can only be made upon knowledge of the weather. Yet the deterministic nature of numerical (traditional) weather forecasting methods (where the state of the system at time $t+1$ is dependent upon the state of the system at time t) disallows their use in the present case, since their accuracy deteriorates beyond a few days into the future. However, the observation of the existence of statistical relationships between the weather-defining parameters of rainfall, vapour pressure, sunshine hours, mean daily temperature and diurnal temperature range provides a solution to the problem, the construction of statistically-equivalent, plausible time series of weather being made possible by the UKCP09 Weather Generator [19]. As a weather generator, whilst it is extremely unlikely that the particular outcome projected in any single run of the model will occur in actuality (ie it cannot forecast the weather), the results obtained through averaging of multiple runs of the model concur with actual projections themselves at the 0.5 probability level (ie the central estimate where temperatures are as likely to be above the forecast value as below the forecast value).

6 Method

The Weather Generator was run 100 times for stationary 99-year time-slices centred on the 2030s (2020-2049), the 2050s (2040-2069) and the 2080s (2070-2099)[9] under low, medium and high

[9] Stationarity – a statistical property which means that little statistical variability is exhibited over the time series ie the 99th year is no less nor more likely to be warmer than the 1st year, any one of which years could represent any of the years within a given grouping (2020-2049, 2040-2069 or 2070-2099).

emissions scenarios for the city centres of three different locations - Edinburgh, Manchester and London - using the UKCP09 Weather Generator.

In order to investigate as broad a span of future climates as possible ranging from a low increase in temperature in a cool climate to a high increase in temperature in a hot climate the three variables were grouped as shown in Table 8.

Table 8 Distribution of variables entered into the Weather Generator

Climate	Outdoor temperature[d]	City	Time slice	Emissions scenario
I	cool	Edinburgh	2030s	low
II	warm	Manchester	2050s	medium
III	hot	London	2080s	high

[d] *The descriptors cool, warm and hot should be viewed as no more than relative terms.*

The Weather Generator was also run for a 1970s control period (1961-1990), observed weather data from which length of time acts as the baseline in the calibration of the Weather Generator in the establishment of the afore-mentioned weather parameter statistical relationships where account is taken of local topographic and coastal influences [19].

Thus 9900 years of daily weather data were produced for each city, averaging of which gives an indication of future climate at the 0.5 probability level (Figure 4).

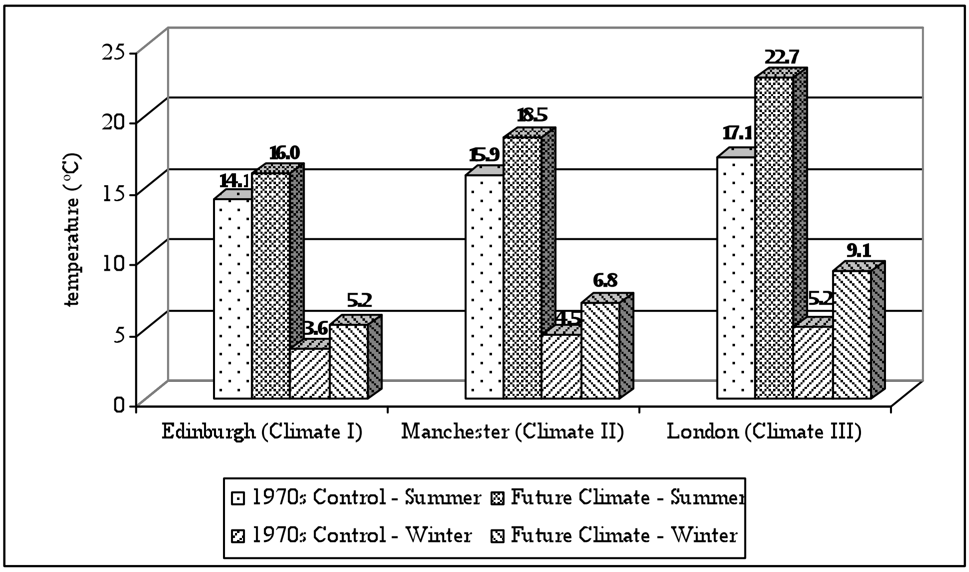


Figure 4 Climate types investigated

The annual number of cooling ACDDs ($ACDD_c$) resulting from implementation of the AAS and the EAS were calculated for the future climates and for the control period using the procedure outlined in Section 3.2. The number of heating ACDDs ($ACDD_h$) were calculated in a similar manner, heating ACDDs representing the extent to which the lower temperature limit of the ACM (ACM_{ll}) dips below the winter PMV base temperature (PMV_{bw}) of 20.0ºC. Table 9 summarises, in equation form, the procedure used to calculate the annual numbers of cooling and heating ACDDs.

Table 9 Summary equations used to calculate ACDD totals

	Cooling ACDDs[e f]	Heating ACDDs[e g]
AAS	$ACDD_c = \left[\sum_{i=1}^{365} (ACM_{ul} - 26.0)\right]/9900$ *where* $ACM_{ul} = 0.31 \times t_{mm} + 17.8 + 3.5$	$ACDD_h = \left[\sum_{i=1}^{365} (20.0 - ACM_{ll})\right]/9900$ *where* $ACM_{ll} = 0.31 \times t_{mm} + 17.8 - 3.5$

EAS	$ACDD_c = \left[\sum_{i=1}^{365} (ACM_{ul} - 26.0)\right]/9900$ *where* $ACM_{ul} = 0.33 \times t_{rm} + 18.8 + 3$	$ACDD_h = \left[\sum_{i=1}^{365} (20.0 - ACM_{ll}))\right]/9900$ *where* $ACM_{ll} = 0.33 \times t_{rm} + 18.8 - 3$

[e] *Indoor temperatures are operative temperatures.*
[f] *when* $ACM_{ul} > 26$
[g] *when* $20 > ACl_{ll}$

In order to more fully examine the effects of different climate scenarios upon the implementation of the standards, the relative performances of the AAS and the EAS were investigated against 18 future Test Reference Years (TRYs) produced by the University of Manchester [20]; developed from 3000 years of future weather data produced by the Weather Generator, the data were prepared in a manner following the ISO standard ISO BS EN ISO 15927 Part 4 (2005). TRYs were produced for:-

- *Edinburgh Turnhouse (rural), high and low emissions scenarios, 2020s, 2050s, 2080s*
- *Manchester Ringway (rural), high and low emissions scenarios, 2020s, 2050s, 2080s*
- *London Heathrow (semi-rural), high and low emissions scenarios, 2020s, 2050s, 2080s*

This is useful as a validation exercise for the robustness of the Weather Generator since the number of ACDDs returned by the TRYs should be broadly predictable with reference to Climates I, II and III; for example, the number of ACDDs yielded by the TRYs for semi-rural Heathrow (2080s, high emissions) should be slightly lower than its central London counterpart (Climate III).

7 Results

7.1 Cooling Season – AAS and EAS

Figure 5 shows the number of ACDD returned by the adaptive standards as the climate warms. Although both the AAS and EAS show an increasing return in the number of ACDDs as one moves from Climate I to III as expected, the differences between the actual numbers of ACDDs are marked: the EAS figures are considerably higher than their AAS counterparts (table 10) for both the control data and the future climate data in all instances.

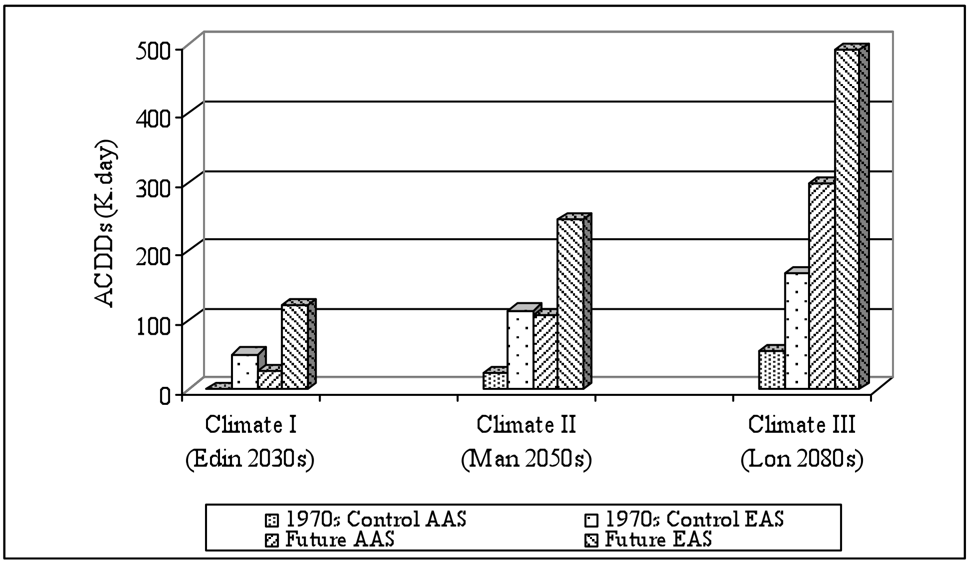
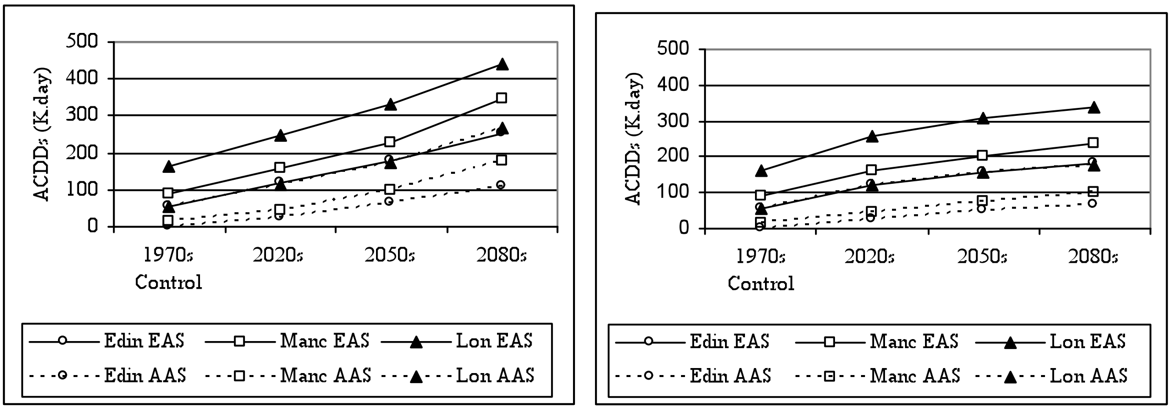


Figure 5 Annual number of cooling ACDDs for 3 climate types with reference to 1970s control

Indeed, even the 1970s control for the EAS returns more ACDDs than does the AAS in Manchester and Edinburgh in the 2030s and 2050s (Climates I and II): not until significant warming beyond the 1950s occurs do yields from the AAS outweigh the EAS 1970s control (Climate III).

The TRY data reveals similarly increasing numbers of ACDDs as the climate warms, but further shows that the differences between low and high emissions scenarios does not start to become appreciable until the latter part of the century: whilst there is very little difference in the number of ACDDs returned between high and low emissions scenarios in the 2020s for all three locations, the difference is very significant by the time the 2080s is reached (figure 6).



(a) (b)

Figure 6 Annual number of cooling ACDDs following implementation of the AAS and the EAS using TRY data for (a) high and (b) low emissions scenarios for Edinburgh (Turnhouse), Manchester (Ringway) and London (Heathrow) for the 2020s. 2050s and 2080s

The data also reveal that, for any given town, potential savings achieved by the EAS (bold line) in any particular decade are not matched by AAS savings (dotted line) until decades later: moving from left to right in figure 6(a) shows that savings achieved in the 2020s by the EAS for either London or Manchester are only matched by the AAS in the 2080s under a high emissions scenario, and figure 6(b) shows that EAS savings in the 2020s outweigh AAS savings in the 2080s for all three towns under a low emissions scenario.

7.2 Heating Season – AAS and EAS

Insofar as the AAS only applies when the mean monthly outdoor temperature is greater than 10ºC, and the EAS only applies when the running mean outdoor temperature exceeds 15ºC, there would appear to be limited scope for the implementation of either standard, in their current form, in winter, over the course of the next century. Analysis of 9900 years of data from the Weather Generator showed that winter (December-February) mean monthly temperatures failed to reach 10ºC for any of the three climates (table 12).

Table 12 Winter mean monthly temperatures (ºC) for three climate types (December, January and February)

	December	*January*	*February*
Climate I	6.1	4.8	4.7
Climate II	7.7	6.3	6.2
Climate III	9.7	8.8	8.7

Although the mean winter temperature failed to exceed the 10ºC threshold for Climates I and Climate II even at the 99th percentile (ie the top 1% mildest winters), the winter mean temperature did, however, manage to exceed the AAS threshold temperature for Climate III at the 71st percentile. Not surprisingly, the EAS threshold running mean temperature was only rarely exceeded; the incidence of such occurrence was negligible for Climates I and II, and was recorded, on average, on less than four winter days for Climate III.

8 Comparison of the AAS and the EAS

It is important to remember that any free-running building is zero-energy, whichever particular label is attached to the adaptive standard being used; a building operating in free-running mode will save exactly the same amount of energy using the AAS as the EAS. The difference between the two standards insofar as energy savings are concerned hinges on the matter of compliance. A building which may be EAS-compliant and can thus save energy through avoiding the use of a mechanical cooling system may not be AAS-compliant; where such non-compliance in the latter case negates the use of the AAS, it will not save energy, unlike its EAS counterpart.

The findings that the upper temperature limits of the thermal comfort zones of the adaptive standards are higher than those of the PMV Model, and specifically, that those of the EAS are higher than the AAS, is expected – such a conclusion could be easily inferred by merely casting an eye over the equations defining the respective comfort zones. The significance of the results lies in the reporting of the extent of the energy savings that can be achieved, and most specifically the speed at which they can be achieved through compliance. The approximate 0.9ºC higher limit of the EAS means that it can be applied to a greater number of buildings, these additional buildings being capable of achieving energy savings at a significantly faster rate than AAS-compliant buildings. As seen, these additional buildings may achieve levels of energy savings in the 2020s which an AAS-compliant building could not achieve until the 2080s or later, irrespective of the emissions scenario chosen.

8.1 Disagreement between Adaptive Standards - Possible Causes

Given the universality of the perception of thermal comfort, it is curious that these two standards should yield such different zones of thermal comfort, the upper limit of the EAS being approximately 0.8-1.0ºC higher than the AAS over the range of climates investigated. Considering the fact that the upper limit of an adaptive standard is often no more than 0.8-1.0ºC higher than the upper limit of the PMV Model, such dissimilitude between the adaptive standards themselves is significant. If claim that the 0.8-1.0ºC difference between the two is insignificant, that there is essentially very little difference between the two adaptive standards, then logic dictates that the same argument should be applied to the ACM theory as a whole, that the 0.8-1.0ºC extension of the upper limit of the PMV Model offered by the ACM may also be ignored, so nullifying the very existence of any adaptive standard in so doing.

Therefore, despite the previously stated requirement that the two adaptive standards be compared on a like-for-like basis, it is apparent that this requirement is not being fulfilled. Two possible causes, one arising from differences in the sample groups/buildings used to draw up the standards, and the other arising from differences in formulation of the adaptive comfort equations, suggest themselves as being responsible for the discrepancy.

8.1.1 Differences in Sample Groups/Buildings

Whereas the free-running buildings used to formulate the EAS may have included non-operational mechanical cooling systems, those of its AAS counterpart did not. In theory this difference could have expressed itself as differences in the degree of adaptiveness shown by occupants, occupants in the former group showing a lesser degree of adaptiveness borne as a result of having occupied the building at some time in the past when it was mechanically cooled. However, the fact that the method used to formulate the European standard, involving the use of the Griffiths constant[10], was designed to eliminate the effects of adaptation, suggests that it is unlikely that such a difference could be an important factor in explaining the difference between the two adaptive standards.

Although the variance may result from any of a number of sources - eg slight differences in experimental procedure on behalf of the researchers, different recent thermal experiences of the occupants, different degrees of adaptive opportunity amongst occupants where perhaps local custom

[10] Gathering together the regression coefficients (from the plots of recorded vote against operative temperature) from a worldwide database of buildings, the Griffiths constant is tantamount to the regression coefficient showing the least/no adaptation. It thus represents the maximum rate of change in comfort vote in response to change in operative temperature, and can thus be used to work out the neutral temperature for any given pair of recorded operative temperature and recorded comfort vote values [4, 21, 22].

limits the extent to which dress code may be altered etc - it may also reflect different racial/cultural preferences, (whether physiological, cultural or psychological in nature), as examined below.

Analysis of the neutral temperatures from occupants in buildings in four different countries used in formulating the EAS [4] shows a degree of variance, being of the order of 1ºC over the range of summer temperatures investigated. Bearing in mind the broad national mix of the RP-884 database, the database from which ASHRAE standard 55 was drawn [7], one might therefore expect to find at least as large a range of neutral temperatures. Perhaps the variance which is averaged out in the countries comprising the EAS database is averaged out differently in the RP-884 database, resulting in different neutral temperatures for the EAS and AAS.

Although climate chamber experiments have reported age, sex and national-geographic (Danish/American) difference as having little affect upon the neutral temperature [23], field surveys have found otherwise. One cannot exclude the possibility that physiological differences in the populations from which the standards were drawn up may partially explain the difference between the two adaptive standards. A significant difference in neutral temperature was found between Japanese and non-Japanese (predominantly North American and European) office workers in Japan who had, on average, lived in Japan for 4.7 years and were thus likely to have acclimatised to local conditions: the difference in neutral temperature was most extreme (3.1ºC) when Japanese females were compared with non-Japanese males [24]. Furthermore, studies reporting on the permanent sensation of cutaneous dryness in black-skinned people living in France as a consequence of reduced levels of sweating [25] add further weight to the argument that differences in physiology (ie race) can lead to differences in neutral temperatures: not violating the biological imperative to maintain a body core temperature of the order of 37ºC (such argument underlying the proposition that race cannot have an effect upon neutral temperature), dark-skinned people may find warmer temperatures comfortable because of an innate preference to sweat more.

8.1.2 Differences in Formulation of Adaptive Comfort Equations

Inspection of the equations in table 3 shows that differences in the number of ACDDs resulting from implementation of each standard may arise because of (a) differences in the neutral temperature for a given outdoor temperature (whether daily running mean or mean monthly), and (b) differences in the temperature bandwidth defining the comfort zone which extends either side of the neutral temperature.

(a) Neutral Temperature

Different approaches are employed in the derivation of the neutral temperature for each standard, the difference between neutral temperatures being in the range 1.3-1.5ºC. A meta-analysis of the individual regression analyses performed on each building was used to determine the neutral temperature of the AAS [7, 26]; the neutral temperature of the EAS derived from a regression analysis involving the use of an adjustment factor related to the Griffiths constant to remove the effect of (i) day-to-day adaptation and (ii) operative temperature error [4].

(i) Whilst the effects of day-to-day adaptation will be manifest in any single building (shown as a reduction in the regression slope when the comfort vote is plotted against the outdoor temperature), this is tempered by the fact that the meta-analysis used in the formulation of the AAS only drew upon neutral temperatures. (The effect of day-to-day adaptation on neutral temperature is less important if the level of adaptation at high temperatures matches the level of adaptation at low temperatures since the regression line will still pass through the same neutral temperature mid-point.) Since the AAS analysis eliminated those buildings which had uniformly hot or cold indoor temperatures [26], it is, therefore, considered that the neutral temperature of the AAS, like its EAS counterpart, is unlikely to have been much influenced by the effects of day-to-day adaptation.

(ii) Whilst the EAS takes specific account of errors arising from the measurement of the indoor temperature and *equation errors* (deriving from the fact that comfort cannot really be described by operative temperature alone), the AAS does not. Although measurement errors are generally small provided good equipment is used [4], one must conclude that it is possible that the equation errors may play some part in explaining the neutral temperature disparity since it is not possible to quantify the magnitude of the equation errors [27].

Differences in ancillary environmental conditions may also partially explain the observed differences in neutral temperature. If, for example, the relative humidity was, on the average, higher in the buildings used to formulate the AAS than in the buildings used to formulate the EAS, it would manifest itself in a lower neutral temperature. Considering the global nature of the RP-884 database used in formulating the ASHRAE standard 55, which includes buildings in tropical climates in south-east Asia and Australia [7], such conjecture cannot be discounted.

The interpretation of *mean monthly temperature* for the AAS is problematic as raised by Nicol and Humphreys [4]. No guidance is given as to the length of time over which the mean should be recorded. The difficulty lies in the fact that as the climate warms, the mean monthly temperature increases – using a mean averaged over the preceding 10 years would result in a lower number of ACDDs than a mean averaged over the preceding 100 years. The assumption implicit in the standard is that the mean is essentially static, that it represents the typical temperature that can be expected at a particular point in time and with which a person is familiar. As such, this criterion is fulfilled in the present study, the mean monthly temperatures being calculated as the mean of that month in the decade under investigation (2030s, 2050s or 2080s) and deriving from 9900 years of data; the mean is not calculated from preceding weather, but rather from weather that can be assumed to be typical of the time[11]. Nevertheless, this is a point for concern.

It has been suggested that the difference between the two standards arises as a consequence of the fact that the AAS uses mean monthly temperatures whilst the EAS uses daily running mean (drm) temperature in the calculation of the neutral temperature. Since the drm temperature on any given day incorporates a measure of the temperature recorded on preceding days, the monthly mean drm temperature will tend to be lower than the monthly mean temperature as the year warms (winter to summer), and higher than the monthly mean temperature as the year cools (summer to winter). Indeed, analysis of the TRY data shows this to be true, that ratio of EAS ACDDs returned in the period August-November compared to March –July[12] being 52:48, July/August being the boundary point where the monthly mean drm becomes larger than the monthly mean temperature (figure 8) (cf the AAS ratio is 47:53). As suggested by these narrow distributions and the symmetry of figure 8 where positive values are counterbalanced by negative values, there is, however, very little difference in the number of cooling ACDDs returned over the course of the cooling season whether one uses monthly mean temperatures instead or drm temperatures, the EAS returning, on average, only 2.7% (range: -0.1 - +6.5%) more ACDDs than the AAS for the 18 TRYs if calculated using monthly mean temperatures instead of drm temperatures.

[11] It should be noted that whilst the present method of calculating the mean monthly temperature is regarded as the best method, the Weather Generator does not allow one to disaggregate data below the decadal level – eg a pattern of weather is projected as occurring in February in the decade of the 2030s, not in a particular year of the 2030s.
[12] No cooling ACDDs are returned outside of these periods.

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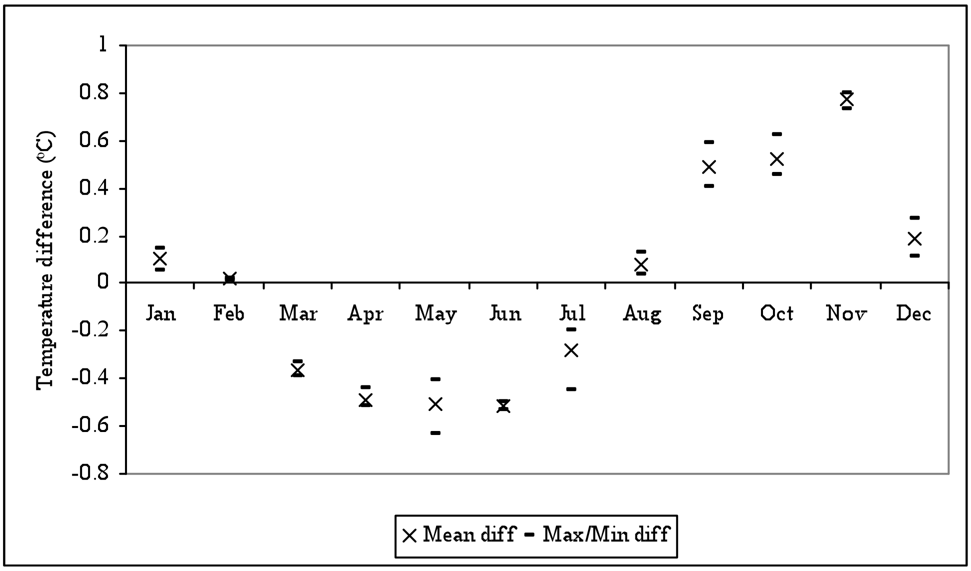

Fig 8 Difference between monthly mean drm temperatures and monthly mean temperatures for 29700 years of future weather data for Climates I, II and III

(b) Width of Comfort Zone

Again, differences in the way that the values *x* and *y* in table 3 are calculated may explain why the comfort zone extends 3.5ºC upwards of the neutral temperature for the AAS, but only extends to 3ºC for the EAS. Both apply the knowledge of the mathematical PMV-PPD relationship that a PMV of 0.5 results in a PPD of 10. The AAS defines the comfort zone width as the average of all the comfort zone widths arising at the 80% acceptability level of all the naturally-ventilated building used to create the standard; the EAS, however, sets the width at ±3ºC of the neutral temperature, such width being the width which would arise in the PMV Model at a PMV of ±0.5 (ie Category B) under typical conditions.[13] Even though, as previously stated, day-to-day adaptation may not have had much impact upon the determination of the neutral temperature for the AAS, its influence will have been felt at the limits of the comfort zone either side of the neutral temperature by virtue of the fact that such limits come from actual measurements taken in the field. This may explain why the comfort zone of the AAS is wider than that of EAS.

Another possible reason for the difference may derive from the posited PPD value of 10 for whole body discomfort which is associated with 80% acceptability in the AAS. Noting the relationship between 80% acceptability and 10% whole body discomfort for the ASHRAE PMV Model, and that an allowance is made for an additional average of 10% dissatisfaction that might occur because of local thermal discomfort, Schiller Brager and de Dear [9] correctly bring attention to the fact that field votes already account for both sources of discomfort in its counterpart 80% acceptability adaptive standard, where occupants naturally integrate both sources of discomfort. Whilst one cannot actually, disentangle whole body comfort from local discomfort, accepting the same PPD value of 10 for whole body discomfort as in the PMV Model is, however, reasonable: use of the alternative 90% acceptability AAS standard produces even more disparity between the upper limits of the AAS and the EAS (since the width of its thermal zone of comfort is only ±2.5ºC).

It should be borne in mind though, that the discrepancy in the width of the comfort zone at the upper temperature limit of the comfort zone is of comparatively minor significance when compared to the difference in neutral temperatures; over the range of temperatures likely to be experienced over the course of the century, neutral temperatures differ by 1.3-1.5ºC, whereas the values *x* and *y* differ by only 0.5ºCwhether the 80% acceptability or 90% acceptability AAS is used.

[13] Typical conditions, as detailed in table A.5 of BS EN ISO 7730:2005, for occupants engaged physical activities with metabolic rates of the order 1.2 met (70W/m^2).

9 Conclusion

The Adaptive Comfort Degree-Day temperature difference/time composite metric introduced in this paper has been used to investigate future climates projected for the United Kingdom over the course of the century with a view to better understanding the implications involved for buildings vis-à-vis energy consumption. In quantifying the extent to which the limits of the thermal comfort zone of the PMV Model can be extended, modelling has shown that the cooling ACDD acts as a good homologue for cooling energy consumption. For buildings in non-humid climates which would otherwise require a mechanical system to maintain comfort levels at 26ºC, the correlation between the number of ACDDs and cooling load approaches parity, indicating its suitability to test the relative competitiveness of adaptive standards. In the present study, the rates at which energy savings can be achieved by (i) the ASHRAE 55 adaptive standard (80% acceptability) [1], and (ii) the European adaptive standard (Category II) [2] have been compared. The legitimacy of the comparison is based not only on the commonality of PPD values at the upper limit of the thermal comfort zone, but also on the grounds that these are the two principal standards bearing the broadest facility to influence design. In view of the fact that the relatively low upper temperature limit associated with the AAS restricts the scope of its application in that fewer buildings will be able to achieve compliance, the EAS is seen to posses much greater potential to yield energy savings, albeit at the expense of a lower degree of thermal satisfaction even though it be deemed comfortable. EAS-compliant buildings allowed to operate at temperatures approximately 0.8-1.0ºC higher than buildings using the AAS can achieve cooling energy savings at a significantly faster rate, such former group of buildings achieving levels of savings in the 2020s which the latter group could not achieve until the 2080s or later. In view of the urgency attached to not only the level but the speed at which carbon emissions must decrease if society is not to suffer the more extreme, deleterious consequence of climate change ,the benefits conferred by the EAS are clear. The study has also revealed that it is very unlikely that winter temperatures will surpass the minimum thresholds necessary to invoke use of either the AAS or the EAS.

The fact that the EAS often extends upon the temperature limits of the AAS to an even greater extent than the AAS extends upon the temperature limits of the PMV Model is reason enough to justify the validity of the present investigation: one cannot possibly discount the temperature differences between the two adaptive standards as being inconsequential. This difference is a cause for concern since the ACM lays itself open to criticism from detractors claiming that the ACM is too imprecise a tool to be considered as a robust alternative to the PMV Model in setting the conditions necessary to guarantee an environment which is considered comfortable. Although a number of possible causes giving rise to the difference between the two adaptive standards have been suggested, more research in this area is required

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