Adaptive thermal comfort and sustainable thermal standards for buildings

J. Fergus Nicol and Michael A Humphreys
Oxford Centre for Sustainable Development, School of Architecture, Oxford Brookes University, Gipsy Lane, Oxford OX3 0BP, UK
jfnicol@brookes.ac.uk

Abstract

The origin and development of the adaptive approach to thermal comfort is explained. A number of the developments in the application of the theory are considered and the origin of the differences between adaptive thermal comfort and the 'rational' indices is explored. The application of the adaptive approach to thermal comfort standards is considered and recommendations made as to the best comfort temperature, the range of comfortable environments and the maximum rate of change of indoor temperature. The application of criteria of sustainability to thermal standards for buildings is considered.

Keywords: Comfort standards, Thermal comfort, sustainability, adaptive approach

1 INTRODUCTION

The definition of acceptable indoor climates in buildings is important to the success of a building not only in making it comfortable, but also in deciding its energy consumption and ensuring its sustainability. In the past the designers of standards have not seen it as part of their task to consider sustainability. With increasing pollution and climate change, standards themselves will fall into disrepute and even disuse if they ignore this issue. Thermal standards which – however desirable they may be – require inordinate amount of energy for their fulfilment will tend to suffer most.

People have a natural tendency to adapt to changing conditions in their environment. This natural tendency is expressed in the adaptive approach to thermal comfort. This paper introduces the adaptive approach and explores some of the recent research bearing upon it. It then suggests ways in which the findings of adaptive thermal comfort can help frame sustainable standards for indoor climate for buildings in the future.

2 ADAPTIVE THERMAL COMFORT

2.1 Field studies and rational indices

The adaptive approach to thermal comfort is based on the findings of surveys of thermal comfort conducted in the field. Field surveys concentrate on gathering data about the thermal environment and the simultaneous thermal response of subjects in real situations, interventions by the researcher being kept to a minimum. The well known early work of Bedford (1936) and the more recent Tropical Summer Index of Sharma and Ali (1986) are examples of this approach. The researcher uses statistical methods to analyse the data using the natural variability of conditions. The aim is to predict the temperature or combination of thermal variables (temperature, humidity, and air velocity) which will be found comfortable. The problems with a field study are firstly that it is difficult to measure environmental conditions accurately and secondly that it is difficult to generalise from the statistical analysis: the results from one survey often do not apply to the data from another even in similar circumstances. An additional problem which has been highlighted by Humphreys and Nicol (2000a) is that errors in the input data can give rise to errors in the relationships predicted by the statistical analysis.

The 'rational' approach to thermal comfort seeks to explain the response of people to the thermal environment in terms of the physics and physiology of heat transfer. An 'index' of thermal comfort is developed which expresses the thermal state of the human body and in terms of the thermal environment. Although the indices were based on the responses of subjects in constant-temperature conditions in climate chambers it was hoped that such an index would express the response of people in variable conditions in daily life.

In fact problems arise when rational indices are used to predict the thermal comfort of subjects from field surveys. Firstly the rational indices require knowledge of clothing insulation and metabolic rate which are difficult to estimate. Secondly they are no better than simpler indices at predicting the comfort vote (Humphreys and Nicol 2001) and the range of conditions which subjects find comfortable in field surveys is much wider than the rational indices predict. The reason for this has been the subject of considerable speculation and research, most of which have concentrated on the context in which field surveys are conducted. Nicol and Humphreys (1973) first suggested that this effect could be the result of a feedback between the comfort of the subjects and their behaviour and that they 'adapted' to the climatic conditions in which the field study was conducted.

2.2 The adaptive principle

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.* This principle links field surveys conducted in a wide range of environments and thus supports meta-analyses of comfort surveys such as those of Humphreys (1976, 1978), Auliciems and deDear (1986) and deDear and Brager (1998). These meta-analyses can be used to draw wide ranging inferences from a number of more restricted thermal comfort surveys.

By linking the comfort vote to people's actions the adaptive principle links the comfort temperature to the context in which subjects find themselves. The comfort temperature is a result of the interaction between the subjects and the building or other environment they are occupying. The options for people to react will reflect their situation: those with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort[1].

---

[1] In these terms the climate chamber is a very particular environment where conditions and occupant action are closely controlled by the researcher for the period of an experiment.

The prime contextual variable is the climate. Climate is an overarching influence on the culture and thermal attitudes of any group of people and on the design of the buildings they inhabit. Whilst the basic mechanisms of the human relationship with the thermal environment may not change with climate, there are a number of detailed ways in which people are influenced by the climate they live in and these play a cumulative part in their response to the indoor climate. The second major context of nearly all comfort surveys has been a building, and the nature of the building and its services plays a part in defining the results from the survey. The third context is time. Human activity and responses take place in a time frame. This leads to a continually changing comfort temperature. The rate at which these changes occur is an important consideration if the conditions for comfort are to be properly specified.

This paper will present findings in all these areas and discuss the implications for the development of more sustainable standards for the indoor climate of buildings.

2.3 People and indoor climate

Nicol and Humphreys (1973) presented data suggesting that the mean comfort vote changed less with indoor temperature from climate to climate than might be expected. Humphreys (1976) confirmed this from a wider variety of climates. The rate of change of comfort vote with temperature is characteristically much lower from one survey to another than it is within any particular survey.

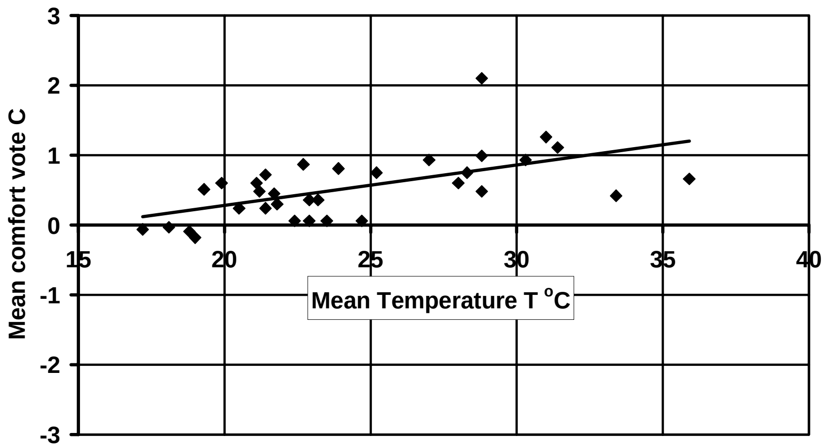

Figure 1 the variation of mean comfort vote with mean indoor temperature. Each point is the mean value from a comfort survey (using data presented in Humphreys 1976).

The corollary of this is that in field surveys the comfort temperature is closely correlated with the mean temperature measured. This was found to be the case in surveys conducted over a wide range of indoor climates (Figure 2a)

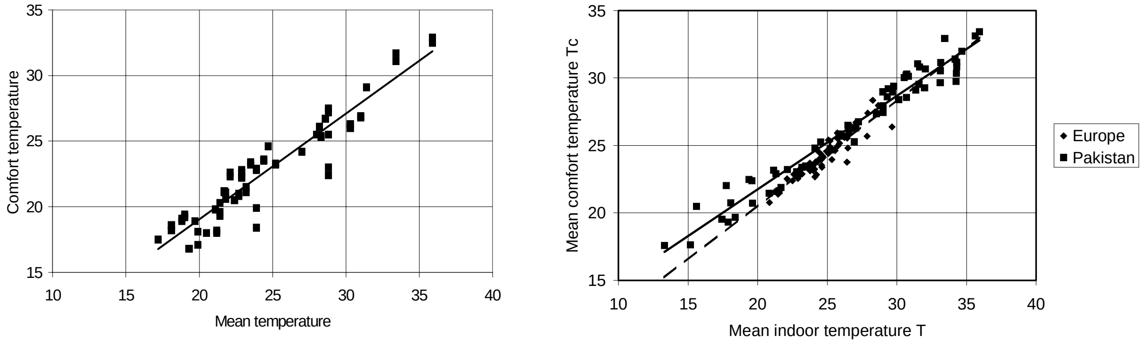

Figure 2 the variation of comfort temperature with mean indoor temperature a) from surveys throughout the world (from data presented in Humphreys 1976) b) from within a particular set of climates (Europe [dashed line] and Pakistan) but at different times of year.

A similar effect was found when data were collected throughout the year from a particular group. Surveys in Pakistan (Nicol *et al* 1999) and Europe (McCartney and Nicol 2001) were conducted at monthly intervals throughout the year (Figure 2b). The variety of indoor temperatures, particularly in Pakistan, is remarkable. The strong relationship with comfort temperature is clear.

As an example of how effectively adaptive actions can be used to achieve comfort, Figure 3 shows the actual proportion of subjects comfortable among office workers in Pakistan at different indoor temperatures. The data were collected over a period of a year so the comfort temperature was continually changing, as was the indoor temperature (Nicol *et al* 1999). The major methods these workers had to control their comfort were by changing their clothing and using air movement, fans being universally available in Pakistani offices. The curve shows the mean probability of comfort calculated using probit regression. Each point represents the proportion comfortable in a particular city in a particular month.

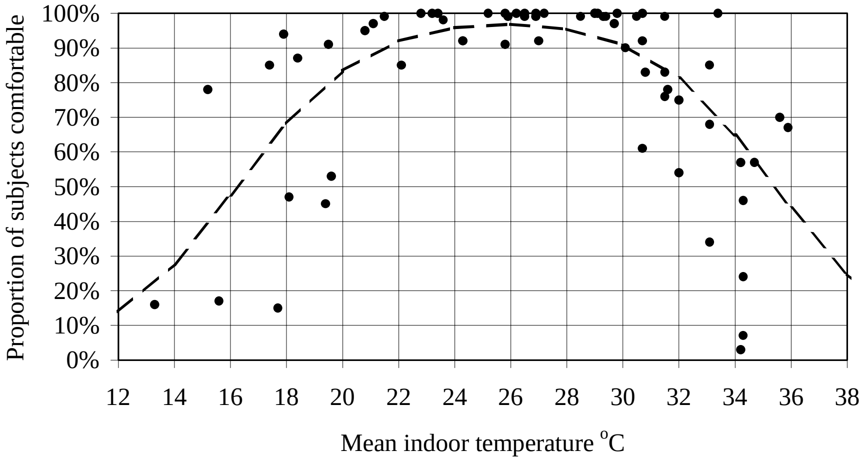

Figure 3. Pakistan: the proportion of office workers who were comfortable at different indoor temperatures. It will be noticed that on many occasions the subjects recorded no discomfort. With a continually changing indoor temperature and comfort temperature Pakistani buildings were found comfortable at temperatures ranging between 20 and 30^{o}C with no cooling apart from fans (from Nicol et al 1999).

2.4 The relationship with outdoor climate

Humphreys (1978) plotted the indoor comfort temperature against the outdoor monthly mean temperature from a number of surveys conducted world-wide. The results are shown in Figure 4. He found a clear division between people in buildings which were free-running at the time of the survey and those buildings that were heated or cooled. The relationship for the free-running buildings was closely linear. For heated and cooled buildings the relationship is more complex.

deDear and Brager (1998) make a division between buildings which are centrally air conditioned and those which are naturally ventilated. They argue that occupants of building which are air-conditioned have different *expectations* than the occupants of naturally ventilated buildings (deDear and Brager 1999). It seems unlikely that people using a building should modify their responses to it on the basis of their expectations of its building services. Nor is this distinction supported by evidence from the field (Humphreys and Nicol 2001). Whilst expectation does have a part to play in the interaction between people and their environment, it is more in defining the temperature they will expect in a particular situation than in their attitude to the building services. More probable is that the difference is due to an accumulation of the small effects caused by a wide variety of adaptive actions which together amount to a large difference in conditions for comfort. In a reanalysis of the data of deDear and Brager, Humphreys and Nicol (2000) argue that the using Humphreys' original distinction increases the precision of the relationship both in free-running buildings and those which are heated and cooled (Fig 5).

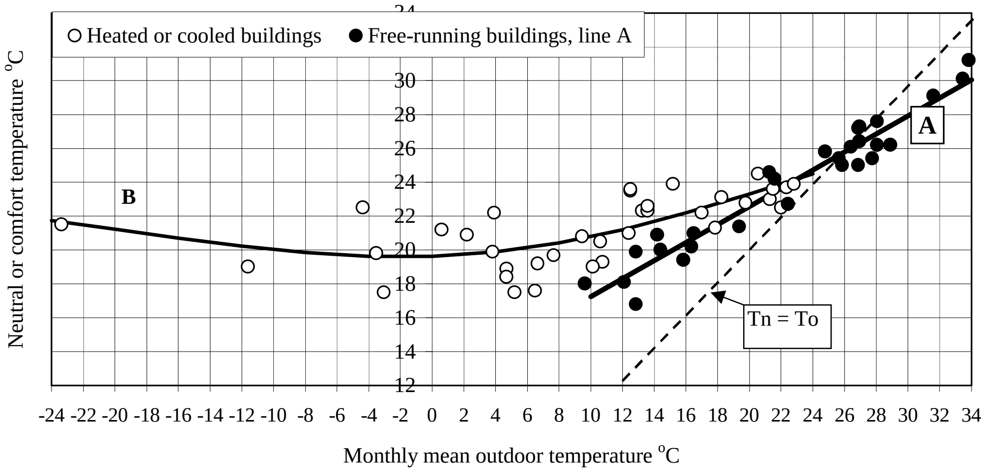

Figure 4. The change in comfort temperature with monthly mean outdoor temperature. Each point represents the mean value for one survey. This graph is from Humphreys 1978. The buildings are divided between those which are heated or cooled at the time of the survey and those which are free-running. Subsequent analysis of the ASHRAE database of comfort surveys (Humphreys and Nicol 2000) showed similar results (see fig 4).

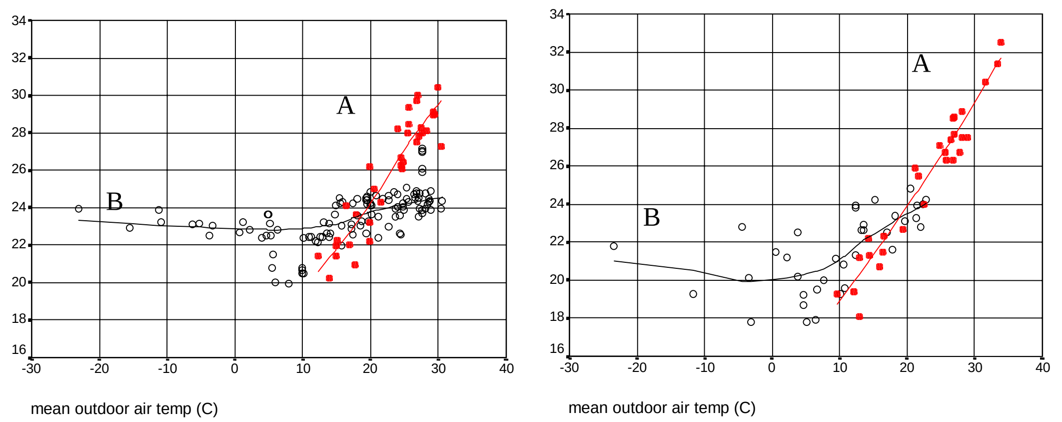

Figure 5. Comfort temperatures as a function of outdoor temperature for buildings which are free-running (A) and with heating and cooling (B). From the ASHRAE database (deDear and Brager 1998) (left) and from Humphreys (1978) (right cf. Figure 4) (diagram from Humphreys and Nicol 2000)

Although only the outdoor temperature is used to calculate comfort temperatures, the comfort temperature is clearly a function of more than that. The clothing insulation also depends on outdoor temperature (Nicol *et al* 1999), as does the use of building controls (Raja *et al* 2001). Other instances are posture, which Raja and Nicol (1997) have shown to vary with temperature, and metabolic rate for a given activity which (Baker and Standeven 1995) suggest may also vary with temperature. It is the *feedback* between the climate and these adaptive actions which means that only the outdoor temperature need be considered in real situations in real buildings. The relationship is to some extent an empirical 'black box' because the inter-relations are not all fully defined.

2.5 People in buildings

Buildings differ in a number of ways. In addition to their individual physical form, they differ in their heating/cooling system and whether it is used, in the possibilities they offer for occupants to control their environment and – in the case of commercial buildings - the polices of management with regard to clothing and other factors. Differences have been found by Humphreys (1978), Busch (1992) and deDear and Brager (1998) between the occupants of buildings which are being heated or cooled and those which are not.

There are other aspects of building services which affect the comfort of occupants. Leaman and Bordass (1997) have demonstrated that there is more 'forgiveness' of buildings in which occupants have more access to building controls. By forgiveness they mean that the attitude of the occupants to the building is affected so that they will overlook shortcomings in the thermal environment more readily. This can be explained as a function of who is in control. Variability is generally thought of as a 'bad thing' in centrally controlled buildings because occupants are adapted to a particular temperature. Much change from this and they become uncomfortable. In buildings where the occupants are in control, variability may result from people adjusting conditions to suit themselves. A certain amount of variability then becomes a 'good thing'. Many NV buildings afford personal control directly to their occupants through openable windows, blinds, fans etc. If the control is left to the building manager (through the HVAC system) there is a smaller envelope of acceptable conditions, comfort changes more quickly with temperature and the occupants appear less forgiving.

Another more robust characterisation is that of Baker and Standeven (1995). They identify an ‘adaptive opportunity’ afforded by a building that will affect the comfort of its occupants. Adaptive opportunity is generally interpreted as the ability to open a window, draw a blind, use a fan and so on, but must also include dress code working practices and other factors which influence the interaction between occupant and building. Many of the adaptive opportunities available in buildings - the use of shading, the reduction of temperature by opening a window and so on - will have no direct effect on the comfort temperature but will allow the occupant to change conditions to suit themselves. Changes in clothing, activity and posture and the promotion of air movement are able to change the conditions which people find comfortable. Actual adaptive behaviour is an amalgam of these two types of action – changing the conditions to accord with comfort and changing the comfort temperature to accord with prevailing conditions. The range of conditions considered comfortable is affected by the characteristics of the building and the opportunities individual adaptation by occupants.

In reality it has been found difficult to quantify the adaptive opportunity in terms of the availability of building controls. Nicol and McCartney (1999) found that the mere existence of a control did not mean that it was used, and that merely adding up the number of controls did not therefore give a good measure of the success of a building or its adaptive opportunity. It would seem that as well as the existence of a control a judgement is needed as to whether that control is useful in the particular circumstances. For example solar shading may be useless on one face of a building, but essential on another. Nicol and Kessler (1998) showed that the usefulness of a particular control could also change from season to season.

The feedback mechanisms embodied in the adaptive principle create order in the relationship between indoor climate and comfort temperature. In a free-running building the indoor climate is linked by the building to outdoor conditions. When the building is being heated or cooled the relationship changes, because the indoor climate is decoupled from that outdoors. In these circumstances the building occupants control comfort temperature either locally as in most naturally ventilated buildings or centrally when the building is centrally air-conditioned.

2.6 Time as a factor in the specification of comfort temperatures

Adaptive actions take time to accomplish. Their rate of change of is characteristically quicker than the fluctuations in the weather from season to season but longer than the fluctuations which take place from minute to minute in the surrounding microclimate. In his comparison between outdoor temperature and the comfort temperature shown in Figure 3, Humphreys (1978) used meteorological records of the monthly mean of the outdoor air temperature as the defining variable. In their analysis of the ASHRAE database, deDear and Brager (1998) use a number of ways to define the mean of outdoor effective temperature without defining the period over which it has been measured. The weather can change dramatically within a month and both people and the buildings they inhabit change at a rate which will not be reflected by a monthly estimate so conditions which are comfortable may be estimated as uncomfortable, and vice versa.

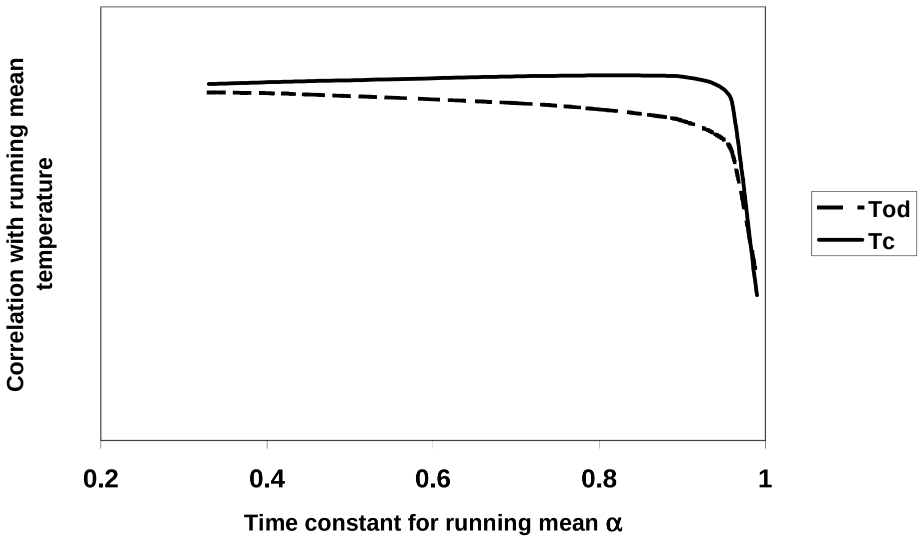

Figure 6. Showing the changing correlation between the exponentially weighted running mean temperature and the comfort temperature (T_c). The serial correlation with the daily mean temperature (T_{od}) is shown for comparison. The measure of the running mean temperature shown is the time constant α (see text).

Recent surveys (Nicol and Raja 1995, McCartney *et al* 1998, McCartney and Nicol 2001) have tried to determine the rate of change of comfort temperature using comfort surveys conducted over a period of time. It may be assumed that the comfort temperature varies as a time-series. Unfortunately comfort surveys do not produce data which is sufficiently coherent for a statistical determination of the best time-series to use. The method used was therefore to assume that an appropriate time series was the exponentially-weighted running mean[2]. The aim is to find the value of α, the time constant, which gives the largest correlation of outdoor running mean with the comfort temperature. Figure 6 shows how the correlation of comfort temperature with running-mean temperature varies with the value of α, the time-constant of the running mean (see footnote). The correlation shows a gradual increase until α reaches about 0.8 and then starts to decrease.

---

[2] Humphreys (1973) suggested that the exponentially weighted running mean of the temperature would be a likely form to reflect the time-dependence of the comfort temperature or clothing on the temperature experienced. The equation for the exponentially-weighted running mean at time t is:

$$T_{rm} = (1-\alpha)\{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} \ldots\} \qquad (1)$$

Were α is a constant between 0 and 1, T_{rm} is the running mean temperature at time t, T_t is the mean temperature for a time t of a series at equal intervals (hours, days etc), T_{t-n} is the instantaneous temperature at n time-intervals previously. The time interval for T_{rm} in this paper it is a day.

This time series gives a running mean temperature which is decreasingly affected by past temperatures as they become more remote. The speed with which the effect of any particular temperature dies away depends on the constant α. The larger the value of α the more important are the effects of past temperatures.

In any real run of outdoor temperatures there will be a serial correlation between the daily mean temperature and the running mean temperature from which calculated from it. Figure 6 shows the correlation of daily mean temperature (T_{od}) with running mean temperature for different values of α. There is clearly a difference in the shape of the two curves suggesting that the comfort temperature curve reflects the way adaptation occurs[3].

Humphreys and Nicol (1995) suggested that an algorithm could be constructed which could determine the indoor temperature to be provided by a HVAC system or a free-running building. This predicts the temperature which would be found comfortable indoors in terms of the outdoor temperature. The algorithm was based on the work done by Humphreys (1978) on the relationship between comfort temperature and the outdoor temperature, but using a mixture of the instantaneous and the running mean - rather than the monthly mean - of the outdoor temperature as the predictor variable. At the time this could only be presented as a tentative proposal. Much work was needed to confirm the exponentially-weighted running mean as an appropriate measure of outdoor temperature for the prediction of comfort temperature indoors. In addition information was needed to help determine the best value of α to use in equation (1) (see footnote 2). Subsequent work has suggested that the instantaneous outdoor temperature adds little to the predictive strength of the running mean temperature. Recent work (McCarthy and Nicol 2001) implies that the use of such variable-temperature control regime does not increase discomfort among occupants, but provides substantial savings in energy use by the air conditioning system.

3 DEFINING AN ADAPTIVE STANDARD

3.1 What kind of standards?

Standards can be divided into those that standardise a methodology and those that define good practice. An adaptive standard will most usefully be of the latter type. Adaptive practice is context dependent. A different standard will be needed for defining temperatures for different circumstances. For example:

- Buildings - indoor comfort conditions to help decide on the design and the sizing of heating or cooling systems or passive strategies
- Comfort conditions outdoors and how to define them (availability of shade, wind speed and direction etc.)
- Vehicle designers – design of air conditioning, ventilation etc

Here we outline the basis for a standard to define good practice in the definition of temperatures in buildings. Such a standard would indicate

- The indoor environments most likely to provide comfort
- The range of acceptable environments
- An acceptable rate of change

The standard needs to help the designer make decisions about likely successful strategies in terms of the building, the controls it provides and its services

[3] Note the scales are different for the two curves which are illustrative

3.2 The most likely comfort temperature

This paper has presented evidence that the comfort temperature in free-running buildings depends on the outdoor temperature as shown in Figure 3. Humphreys and Nicol (2000) have shown that for free-running buildings the relationship between comfort temperature T_c and outdoor temperature T_o is remarkably stable (figure 5).

Both studies give an equation for comfort temperature close to

$$T_c = 13.5 + 0.54\ T_o \qquad (2)$$

Where T_o in this case as the monthly mean of the outdoor air temperature.

The relationship for buildings which are heated or cooled is more complex, and less stable. It is less precise because when a building is heated or cooled the indoor temperature is decoupled from the outdoor temperature and the indoor temperature is more directly governed by the custom of the occupants (or their building services manager). This custom is not absolute as is shown by the wide range of comfort temperatures for heated and cooled buildings shown in figures 4 and 5. There is also a difference of some 2^oC in indoor comfort temperatures for heated and cooled buildings between the two databases from Humphreys in 1978 and deDear and Brager in 1998 (see figure 5). Whilst it is not clear whether this is due to a change in preference over time or to other differences between the two databases, the preferred indoor temperature may need to be determined from time to time or between one group of people and another. It should be noted that this does not put the adaptive standard at a disadvantage vis-à-vis the rational indices. These also need to know of changes of clothing behaviour and working practices if they are to reflect changes in comfort temperatures.

3.3 The range of comfortable conditions

Defining the range of conditions which will be found comfortable around the comfort temperature is problematic. The adaptive approach tells us that variability in indoor temperatures can be caused by actions taken to reduce discomfort, as well as those which are uncontrolled and therefore more likely to cause discomfort. Adaptive thermal comfort is therefore a function of the possibilities for change as well as the actual temperatures achieved. The width of the comfort 'zone' if measured purely in physical terms will therefore depend on the balance between these two types of action. In a situation where there was no possibility of changing clothing or activity and where air movement cannot be used, the comfort zone may be as narrow as $\pm 2^oC$. In situations where these adaptive opportunities are available and appropriate the comfort zone may be considerably wider.

3.4 Using the standard to design buildings and their services

The adaptive relationship between comfort temperature and the outdoor temperature can be used to help design comfortable buildings. An example is shown in figure 7. Here the indoor comfort temperature is calculated from the mean outdoor temperature and plotted on a monthly basis together with the monthly mean of the daily outdoor maximum, minimum and mean air temperatures. Such a diagram helps the designer to judge whether passive heating and/or cooling are a possibility in the climate under consideration. The relationship between the desired indoor temperature and the range of outdoor temperatures shows whether, for instance, night cooling is likely to be a viable way to keep the building comfortable in summer, or to calculate whether passive solar heating will be enough in winter. This method has been used by Roaf *et al* (2001) to define comfort indoors in a recent book.

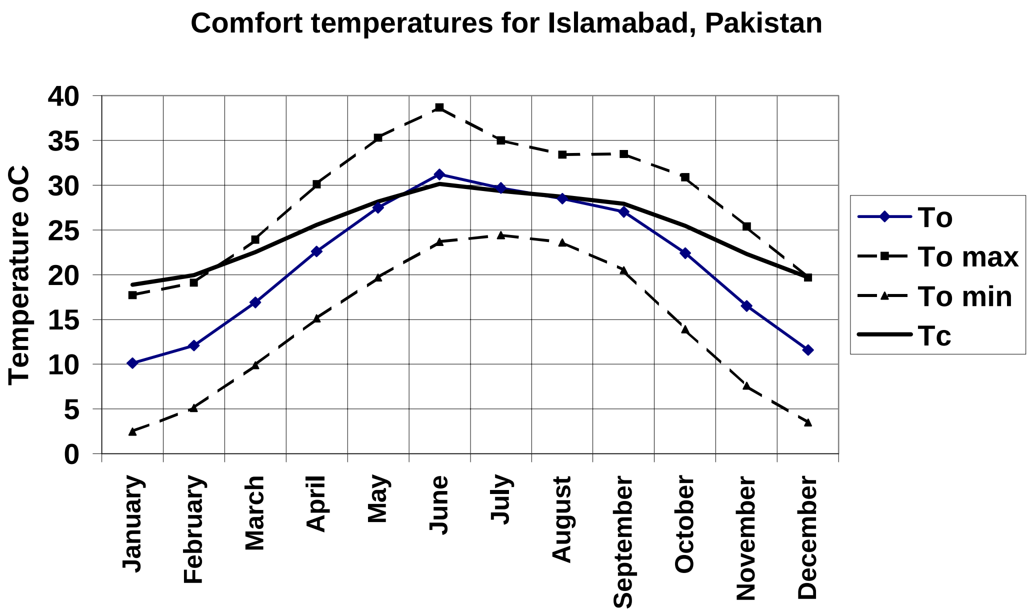

Figure 7. Showing the seasonal changes in mean comfort temperature Tc in Islamabad, Pakistan and its relation to mean daily maximum, minimum and mean outdoor temperatures To. The relationship used to calculate comfort temperature from outdoor temperature is from Humphreys (1978) for free running buildings

3.5 The case of heated and cooled buildings – the adaptive algorithm

The comfort temperature in heated or cooled buildings is a matter of custom but so long as the change is sufficiently slow, people will adapt to a range of temperatures. The indoor comfort temperature will naturally change with the seasons as people adjust their clothing with the weather. Thus the idea of an ‘adaptive algorithm’ (Humphreys and Nicol 1995) which defines a variable indoor temperature in terms of the running mean of the outdoor temperature is attractive. A crude form of such an algorithm is already used in ASHRAE standard 55 (ASHRAE 1992) which describes different indoor set points for ‘summer’ and ‘winter’. These seasonal set-points are based on crude assumptions for clothing insulation and metabolic rate. The adaptive algorithm changes continuously in line with measurements from comfort surveys and does not rely on the vague description of ‘season’ but relates the set point directly to the running mean of the current outdoor air temperature. A recent project (McCartney and Nicol 2001) suggests that such a variable indoor standard does not increase occupant discomfort, yet does significantly reduce energy use by the cooling system compared to a constant indoor temperature.

3.6 Sustainable comfort standards

One aim of this paper is to introduce the notion of Sustainable Comfort Standards. Whilst accepting that a standard which significantly reduces comfort will be no more sustainable than one which increases energy use, there is nonetheless much to be gained when presented with two otherwise equal possible standards, for preferring the one which is more sustainable. A number of attempts have been made through simulation (e.g. Milne 1995, Wilkins 1995) to predict the changes in energy use which will result from the use of a variable indoor temperature in air conditioned buildings and most have suggested that energy savings will result. The extent of energy savings has been estimated in the region of 10% of the cooling load in UK conditions. In a recent European project (Stoops *et al* 2000) estimated energy savings were in the region of 18%.

Naturally ventilated buildings typically use about half the energy of ones which are air conditioned (Kolokotroni *et al* 1996). The temperatures in free-running naturally ventilated buildings are constantly changing in line with outdoor conditions. A constant-temperature standard therefore militates against the use of natural ventilation. A variable indoor temperature standard will help save energy by encouraging the use of naturally ventilated buildings. Note that, though it will save energy in an air conditioned building, a 'seasonal' temperature change such as is suggested by ASHRAE 55 (ASHRAE 1992) may be almost as hard to achieve in a free-running building as a single constant temperature throughout the year.

4 CONCLUSIONS

This paper explores the use of results from the field to inform thermal standards in buildings.

1) Field studies suggest that rational indices are difficult to use in real situations and are poor indicators of comfortable conditions in buildings. This suggests that relationships based on laboratory experiments should be tested in the field before inclusion in standards.
2) The adaptive approach allows building designers to estimate the indoor temperature which building occupants are most likely to find comfortable, particularly in free-running buildings.
3) There are a number of small ways in which people can adapt to their environment. People use these adaptive mechanisms or opportunities to achieve their desired conditions. The cumulative effect of these adjustments can explain the differences between the responses of people buildings with different servicing regimes and levels of available control.
4) The range of conditions which will be found acceptable at any one time is in the region of $\pm 2^{o}$C. Giving occupants the control necessary to make themselves comfortable can increase this range.
5) The building should give occupants the chance to adjust the conditions to suit themselves. Discomfort is increased if control is not provided, or if the controls are ineffective, inappropriate or unusable.
6) The rate of change of comfort temperature can be characterised by the running mean of the outdoor temperature. This means that an adaptive algorithm can be

formulated which can be used to calculate a variable indoor set-point, related to the outdoor temperature. Early indications are that such a variable set-point does not increase discomfort and allows significant reductions in energy use in buildings.

7) Sustainability needs to be considered in the framing of standards. Such standards can have an effect on the energy use by buildings. Were acceptable low-energy solutions are available they should be preferred.

And finally… do we really need to specify indoor climate?

This paper has made the case that optimal indoor environments in a building are a function of its form, the services it provides and the climate in which it is placed. This implies that, given a full understanding of the mechanisms at work, it may eventually be possible to produce thermal standards for building which do not resort to specifications of the indoor climate. The characteristics of a building (in terms of controls and building management) in relation to the local climate may be sufficient. Such standards will be more meaningful to building designers and consequently will be more likely to be used.

5. REFERENCES

ASHRAE (1992) *Standard 55 – Thermal Environment Conditions for Human Occupancy,* American Society of Heating Ventilating and Air-conditioning Engineers, Atlanta, USA

Auliciems, A. and deDear, R. (1986), Air conditioning in Australia I; Human thermal factors. *Arch Science Review 29, 67-75*

Baker, N.V. & Standeven, M.A. (1995). A behavioural approach to thermal comfort assessment in naturally ventilated buildings. Proceedings CIBSE National Conference, Eastbourne, pp 76-84.

Bedford, T (1936) *The warmth factor in comfort at work*: MRC Industrial Health Board Report No 76 HMSO

Busch J. (1992). A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand: Energy and Buildings Vol 18 235-249

deDear, R.. (1998) A Global database of thermal comfort field experiments. *ASHRAE Transactions* 104 (1)

deDear, R. & Brager, G. (1998) Developing and adaptive model of thermal comfort and preference. *ASHRAE Transactions* 104 (1)

Humphreys, M. A. (1973) Clothing and comfort of secondary school children in summertime. *Thermal comfort and moderate heat stress, proceedings of CIB commission W45 (Human Requirements).* HMSO

Humphreys, M.A. (1976). Field studies of thermal comfort compared and applied. *J. Inst. Heat. & Vent. Eng. 44,* pp 5-27.

Humphreys, M.A. (1978) Outdoor temperatures and comfort indoors. *Building Research and Practice (J CIB),* 6(2) pp 92-105.

Humphreys, M. A. and Nicol, J. F. (1995) An adaptive guideline for UK office temperatures. in *Standards for thermal comfort: indoor air temperature standards* *for the 21st century. (Ed. Nicol JF, Humphreys MA, Sykes O and Roaf S)* London, E & FN Spon

Humphreys, M.A. and Nicol, J.F. (2000) Outdoor temperature and indoor thermal comfort: raising the precision of the relationship for the 1998 ASHRAE database of field studies *ASHRAE Transactions* 206(2) pp 485-492

Humphreys M.A. and Nicol J F (2000a) The effects of measurement and formulation error on thermal comfort indices in the ASHRAE database of field studies *ASHRAE Transactions 206*(2) pp 493-502

Humphreys, M.A. and Nicol, J.F. (2001) The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Paper to this conference.*

ISO (1994) *Moderate thermal environments – determination of the PMV and PPD indices and specification of the conditions for thermal comfort* International Organisation for Standardisation, Geneva

Kolokotroni, M., Kukadia, V. and Perera, M.D.A.E.S. (1996): NATVENT - European project on overcoming technical barriers to low-energy natural ventilation, *Proceedings of the CIBSE/ASHRAE joint national Conference 1996* Chartered Inst. of Bldg Serv. Engrs, London

Leaman, A.J. and Bordass, W.T. (1997) Productivity in Buildings: the "Killer" Variables, *Workplace Comfort Forum*, London, U.K.

McCartney, K. J., Nicol, J. F. and Stevens, S. (1998) Comfort in office buildings: results from field studies and presentation of the revised adaptive control algorithm. *Proceedings of CIBSE National Conference Bournemouth*, Chartered Institution of Building Services Engineers, London UK

McCartney, K.J. and Nicol, J.F. (2001) Developing an adaptive control algorithm for Europe: results of the SCATS project. *Paper to this conference*

Milne, G.R. (1995) The energy implications of a climate-based indoor air temperature standard in *Standards for thermal comfort: indoor air temperature standards for the 21st century. (Ed. Nicol JF, Humphreys MA, Sykes O and Roaf S)* London, E & FN Spon

Nicol, J.F. (2000) Time and thermal comfort, evidence from the field *Renewables: the energy for the 21st century WREC VI, Brighton, 2000 (ed Sayigh), part 1 pp477-482*, Pergammon Press, Oxford, ISBN 0 080 43865

Nicol, J.F. and Humphreys, M.A. (1973) Thermal comfort as part of a self-regulating system. *Building Research and Practice (J. CIB) 6(3), pp 191-197*

Nicol, J.F. and Kessler, M.R.B. (1998) Perception of Comfort in Relation to Weather and Adaptive Opportunities, *ASHRAE Transactions vol. 104 (1) 1005-1017*

Nicol, J.F. and McCartney, K.J. (1999) Assessing adaptive opportunities in buildings. *Proceedings of the CIBSE National Conference* pp219-229 Chartered Institution of Building Services Engineers, London

Nicol, J.F. and Raja, I.A: (1995) Time and thermal comfort in naturally ventilated buildings *Symposium on passive cooling of buildings*, Athens June 1995

Nicol, J.F., Raja, I.A., Allaudin A. and Jamy, G.N. (1999) Climatic variations in comfort temperatures: the Pakistan projects *Energy and Buildings 30(1999) 261-279*

Nicol, J.F and Sykes, O.D. (1998) Smart controls for thermal comfort, the SCATS project *Proceedings of the EPIC 98 Conference, Lyon*, Vol 3 pp844-849

Raja, I.A., Nicol, J.F. and McCartney, K.J. (2001) The significance of controls for achieving thermal comfort in Naturally Ventilated buildings. *Energy and Buildings* ***33*** *pp 235-244*

Raja, I.A. and Nicol, J.F. (1997) A technique for postural recording and analysis for thermal comfort research *Applied Ergonomics Vol. 27 (3) pp. 221-225*, Elsevier Science Ltd., London 1997

Roaf, S.C., Fuentes, M. and Taylor, S. (2001) *The Eco-house design Guide.* Architectural Press, London ISBN 0 7506 4904 0

Sharma, M.R. and Ali, S. (1986) Tropical Summer Index – a study of thermal comfort in Indian subjects. *Building and Environment* **21 (1)** pp 11-24

Stoops, J. Pavlou, C., Santamouris, M. and Tsangrassoulis, A. (2000) *Report to Task 5 of the SCATS project (Estimation of Energy Saving Potential of the Adaptive Algorithm)* (Contract no JOE3CT970066) European Commission

Wilkins J. (1995). Adaptive comfort control for conditioned buildings*. Proceedings CIBSE National Conference*, Eastbourne. 2, pp 9-16