The range and shape of thermal comfort and resilience

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Abstract: The adaptive approach to thermal comfort shows that there is not a single comfortable temperature. A wide range of the temperatures which occur in indoor environments can be found acceptable to building occupants depending on their individual experiences and circumstances. This paper extends the approach introduced in a recent paper [1] to learn the lessons which can be drawn by looking in detail at the relationship between indoor and outdoor temperatures in buildings. By reviewing the records of indoor and outdoor temperatures from field surveys in a variety of climates and cultures, the paper explores the limits to the acceptable indoor temperature range, and its relationship to the concurrent outdoor temperature. In doing this the paper builds on past findings adding some related lessons derived from surveys from many parts of the world – especially Japan, Pakistan, Nepal and Europe. The ways in which the shape of a cloud can be interrogated are explored as well as the effect of emergencies on the range of acceptable temperatures in buildings.

Keywords: Indoor temperature, Outdoor temperature, Thermal comfort, Acceptable temperatures

1. Introduction: looking at temperature clouds in buildings

The adaptive principle says that, in a room or a building, *"if a (thermal) change occurs such as to produce discomfort, people react in ways that tend to restore their comfort"* [2]. There is a negative feedback system operating between the occupant and their environment that tries to ensure that the occupants' interaction with the environment will tend to reduce any discomfort. The relationship between indoor and outdoor temperatures in buildings reflects a further, complex, feedback system in which the indoor environment is the result of the outdoor conditions, as acted upon by the building, its services and its occupants. The occupants use the means at their disposal - the available *adaptive opportunities* [3] - to make themselves less uncomfortable. The whole amounts to a complex feedback system – a system which can have multiple optima [2- Ch 12].

If we assume the purpose of mechanical conditioning (heating or cooling) is to give a constant indoor 'comfort temperature', as is assumed in guidance and standards, then this suggests that a constant indoor temperature will be found in conditioned buildings. Nicol [1] explored data from several countries which demonstrated that the range of indoor temperature in heated and cooled (conditioned) dwellings can often be greater than is found in the same dwellings when they are not conditioned.

The analysis used by Nicol [1] was to establish 'temperature clouds' of the data. These clouds are areas within the two-dimensional indoor/outdoor temperature space which show, for a particular building or group of buildings, the indoor temperatures which actually occur at the concurrent outdoor temperatures. This approach, mapping the raw data collected in a field survey, is different to the more usual approaches where statistical analysis is used to reduce a wide spread of field data to standardised comfort responses such as neutral temperatures.

The aim of a traditional thermal comfort survey, particularly in buildings which are being heated or cooled (mechanically conditioned), is to identify a 'comfort' or 'neutral' temperature that will minimise the discomfort of the building occupants. This approach assumes that there is a constant, or narrow, indoor 'comfort temperature', or 'comfort range', to be sought and provided to building occupants. The data used in Nicol [1] showed that this approach over-simplifies the way people use energy to control indoor conditions.

This paper uses the 'temperature clouds' approach to look at, among other things, the relationship between indoor and outdoor temperature in buildings. The method seeks to avoid some simplifications inherent in using statistics. A rational approach taken too literally can give a mistaken impression of the precision of the relationships being investigated. In addition, many of the accepted statistical relationships assume a specific distribution of the results such as the value of the neutral temperature and the assumption of an accepted distribution of their range. Data such as that collected in field surveys related to actual physical phenomena often do not occur in such an ordered stochastic way and therefore the accepted relationships may give misleading results. In many cases the error introduced by this approximation will be small, but it should be borne in mind.

In addition, the use of linear statistics to look at the interrelations between physical measurements and subjective impressions means that a part of the interrelation is lost to the model. These methods, developed from physical models, are useful to the approach used by building services engineers who want a single figure to represent 'comfort' in their design calculations but when applied in the interpretation of the comfort surveys in the field can mean a lot of the collected data may be lost in the model. If the data collected in the field is wide-ranging and complex, why give the results solely in terms of indoor temperature? Each part of the interrelation is correlated to others in ways which could themselves be complex. These interrelations are contained within the cloud and can be explored in the ways suggested by figures such as those numbers 7-10 in this paper and in the sections which follow them.

The comfort vote is measured and various indices have been developed based on the thermal properties of the environment to predict the value of the comfort vote. The most famous of these is Fanger's [4] predicted mean vote (PMV) but others are Effective Temperature (ET), Standard Effective Temperature (SET), and Operative temperature (T_{op}) which combines radiant temperature and air temperature and of course air temperature (T_a) itself. Each of these requires the measurement of a number of physical (and personal) variables which, if they are combined in the correct way are expected to get an increasingly precise fix on the comfort vote. Table 1 shows, for two databases the ASHRAE (I) [5] and the European SCATs, [6] the correlation between the comfort vote given by the subjects and the calculated value of each index. Remarkably, the more physical measurements required to calculate the index, the lower the correlation between comfort vote and the index seems to be.

Table 1. Correlation of the comfort vote with a variety of indices together with the number of variables which need to be measured to calculate the value of the index (after [7])

	T_a (°C)	T_{op} (°C)	ET* (°C)	SET (°C)	PMV
ASHRAE I	0.514	0.515	0.507	0.430	0.462
SCATs	0.352	0.333	0.319	0.200	0'249
No variables	1	2	3	6	6

Humphreys et al. [7] comment: "The rational indices do not improve upon the air or globe (T_{op}) temperatures. ET* is a little inferior while SET and PMV are considerably inferior. So the theoretical advantage of including all 6 variables does not produce a practical improvement, instead there is a deficit. This is attributable jointly to imperfections in their formulaic structure and error in the measurement of their constituent variables."

The clouds approach includes, in most cases, far more than the standard six variables[1]. These were used to derive the model which underlies PMV, all of them internal to the laboratory space from which the model was developed. There is no allowance for contact with the outside, for the weather or the use of adaptive opportunities. These may be the key constituents of the comfort model which are missing but which can be crucial – consider the effect in the indoor comfort of opening a window… In the cloud approach most variables are there: the trick is to discover which are important and which merely to confuse the issue.

Nicol [1] using data from a range of climates suggests that people can be comfortable in a wide range of temperatures in mechanically conditioned and in free-running dwellings. The reason for the wide range in conditioned dwellings was the individual differences in clothing worn, income and lifestyle as well as differences in physiology and body build. In buildings which are free-running, occupants can find ways to suit the environment to their own preferences (through changes in air movement, shading, windows etc.) or to suit themselves to their environments (changes in clothing, posture, activity etc.). Using those adaptive opportunities at their disposal they can match their local environment to their own temperature preference by one or other strategy, or by a mixture of several.

The range of acceptable environments is often smaller in free running than in conditioned buildings where the use of energy enables the building occupants to make big changes in the environment. In a free-running building the range of indoor temperatures is determined by the physics of the building and the weather outside. In this paper temperature clouds are used to indicate the limits of the acceptable range of indoor temperatures as derived from the results of field surveys of thermal comfort. In doing this the shapes and extent of the temperature clouds give information about the ways in which indoor and outdoor temperatures interact and indicate something of the way the system is controlled by the buildings, their services and their occupants.

Limiting 'allowable temperatures' may lead to excluding those that might be encountered in unusual, or extreme, conditions such as power outages, heat waves and so on. When existing mechanical heating or cooling is inadequate to deal with conditions that they were not designed for, this may result in discomfort. Such emergency conditions are predicted to become increasingly common as extreme weather arises more frequently as a result of extreme events related to climate change and need to be borne in mind.

[1] Air and radiant temperature, air speed and moisture content, mean clothing insulation and metabolic rate.

1.1. Comfort in conditioned and free-running buildings

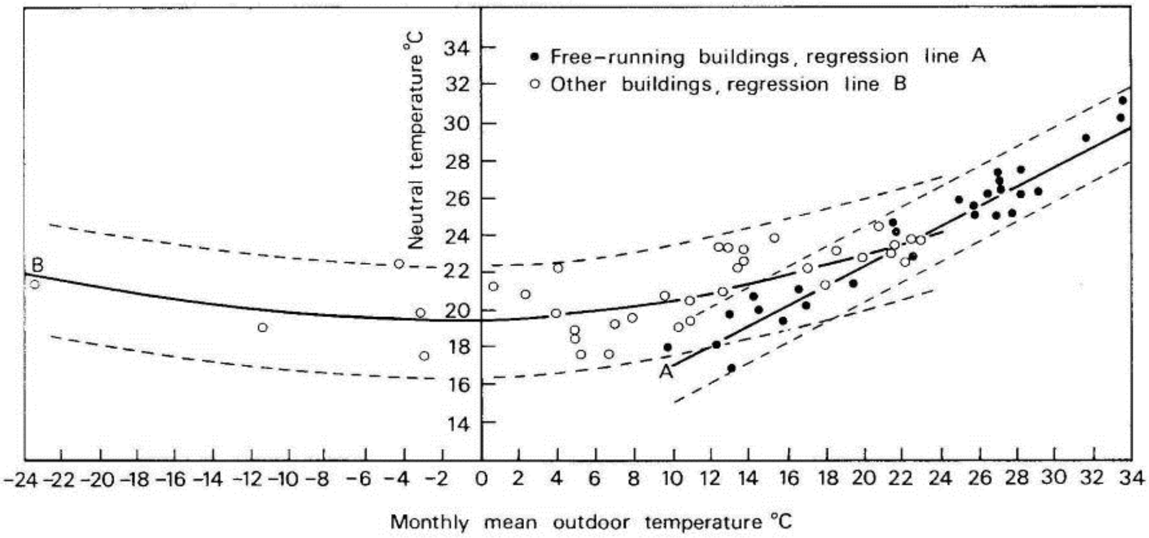

Figure 1. The relationships demonstrated by Humphreys between mean indoor neutral or comfort temperature and mean outdoor temperature. Each mark in the graphs is the product from a whole field survey from Humphreys [8]

Humphreys [8] investigated the relationship between the indoor neutral temperature and the prevailing outdoor temperature. In conditioned buildings the neutral temperature, though essentially independent of the outdoor temperature, varies so that the mean neutral temperature rises on either side of 0^{o}C. The effect is shown in Figure 1. In heated buildings this increase in indoor temperature might be to compensate for the increasingly inhospitable outdoor climate, and in cooled buildings it may result from the acclimatisation of the occupants, or maybe because occupants need to allow for the inefficiency of the cooling system. Most remarkably he found that the neutral [2] temperature in free-running buildings was linearly related to the outdoor temperature. The strength of this linear relationship has become generally accepted and is used in standards such as ASHRAE 55 [9] and EN15251 [10] to predict conditions for comfort in free-running buildings.

1.2. Variability in comfort data

2 The Neutral Temperature is the temperature at which the comfort vote is most likely to be 'neutral' on the ASHRAE scale. This is often referred to as the 'comfort temperature'.

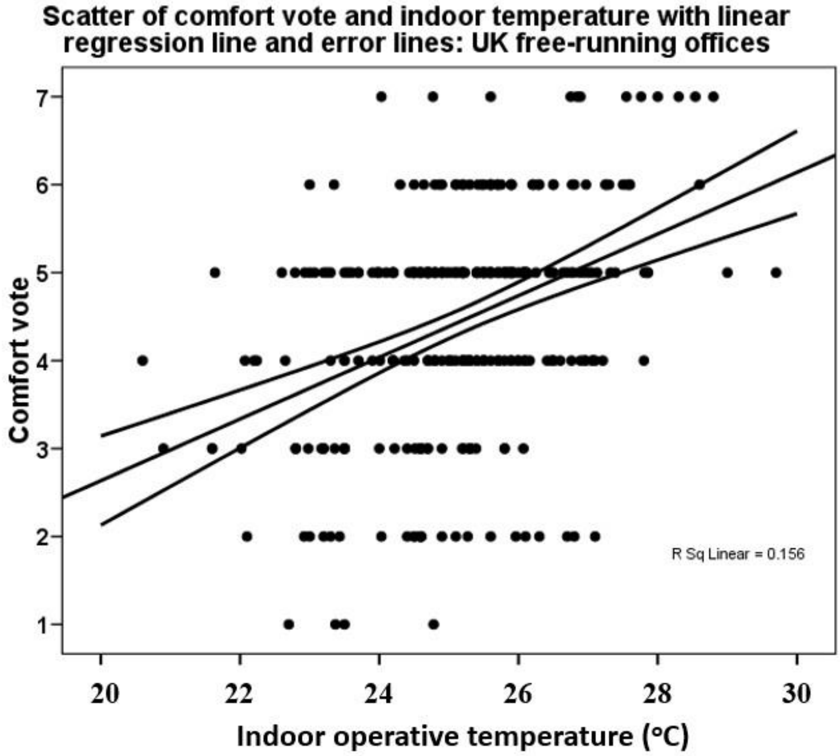

Figure 2. Showing the values of the comfort vote and the operative temperatures for 233 responses from UK subjects over 5 months in two free-running offices in the SCATs project. The mean globe temperature Tg is 25.0 °C Mean comfort vote 4.39 and neutral temperature is 23.9 °C. from Nicol et al.[11]

Figure 2 presents a graph of comfort vote against the indoor operative (or globe [3]) temperature from UK subjects in the European SCATs project [6]. Each point on the graph is the value of a single comfort vote on the Bedford scale and the temperature of the space the subjects occupied at the time the vote was cast. Note that the many comfort votes and indoor temperature in figure 2 would be reduced to a single point and a lot of potential information lost if analysed using the method used in Figure 1.

Figure 2 suggests that some 84% (R^2 = 0.16) of the variation on the comfort vote is not explained by the indoor temperature alone. Nicol et al. [6 ch10] show how by dividing the data into separate months some of this dispersion can be explained. Shipworth et al. [12] argue that "understanding diversity is important, both practically and scientifically, and that to do so we need to address the physiological, psychological, social, cultural and built-environmental conditions that give rise to observed diversity in comfort". They identify a number of causes of diversity, but the quantification of each, and the question of whether they work in sympathy, or antagonistically, is a subject in need of further research.

This paper is concerned with the range of temperatures which actually occur in buildings. We can assume that occupants find these conditions liveable. Rather than looking at the temperature(s) which give the optimum, or 'comfort' temperature, at which occupants will be most likely to feel comfortable, we are looking at the range of temperatures that occupants actually do experience, and therefore can assume, they find acceptable in their own living spaces. Nicol [1] shows that for the majority of the time, appropriately acclimatised subjects will find the temperatures acceptable.

3 The operative temperature is a theoretical mixture of air and radiant temperature which combines their separate effects. The globe temperature is usually an acceptable approximation.

2. Temperature clouds in buildings with mechanical conditioning

The results described in this paper seek to demonstrate a trend, rather than trying to set up a precise description of a phenomenon which is, in any case, imprecise and changeable. Figure 3 introduces the idea. The plot is shown of all the concurrent indoor and outdoor temperatures collected in a SCATs survey in five air-conditioned Swedish offices. The temperatures appear as an area or cloud in the indoor/outdoor temperature graph which comes from the SCATs data [6]. The clouds differ for the five buildings but in this case the differences are small. In these conditioned buildings the indoor temperatures have been purposely kept approximately constant to comply with the narrow range considered appropriate in air-conditioned buildings. European standard EN 15251 [10] recommends indoor temperatures in mechanically conditioned offices of 20-25°C in winter and 23-26°C in summer.

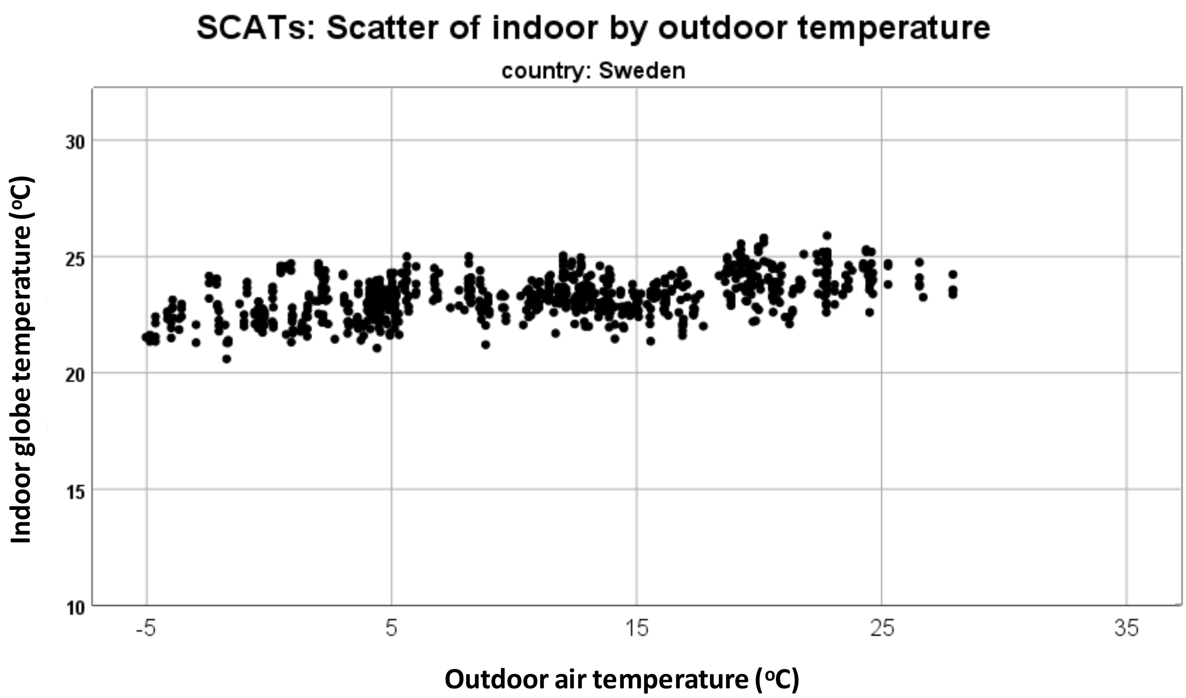

Figure 3. Temperature cloud for closely controlled office buildings in South western Sweden. There is a slight upward linear regression slope of 0.05 with a coefficient of concordance R^2 of 0.224. 94% of subjects voted they were comfortable

The indoor temperature is not absolutely independent of outdoor temperature. As well as a random variation of about ±2.0K or less, indoor temperature increases gradually with increasing outdoor temperature. This is in line with the kind of variability suggested in the discussion of Figure 1. Similar 'clouds' can be constructed for other indoor spaces.

The clouds from the different surveys are not all strictly comparable. All results in this section of the paper are from buildings which are being heated and/or cooled at the time of the survey. Some are measurements taken in one season, and some in another, some relate to buildings which are mechanically cooled, and some which are heated. Some are from a particular building type, some include data which are collected from several buildings in a particular season, or city, and some from a single building. The data which form the clouds are nevertheless all from occupied buildings measured at the time when the survey subjects cast a comfort vote. The aim is to see whether there is a pattern in the occupied buildings, and whether there is evidence of what indoor temperatures are acceptable for habitation.

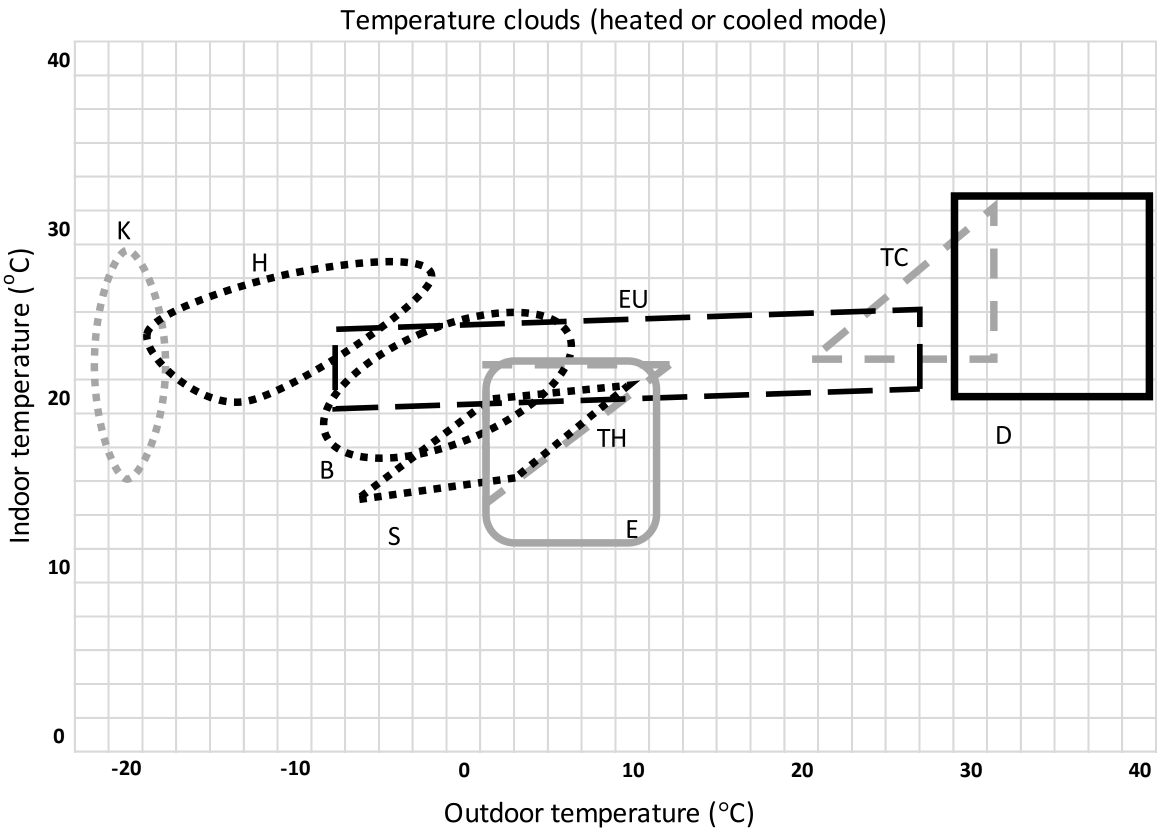

Figure 4. Temperature clouds from surveys in various parts of the world from buildings which were mechanically cooled or heated at the time of the survey. Key: Black dotted: China (Harbin (H), Beijing (B), Shanghai (S) in winter [13], dotted grey: Russia (Khabarovsk winter K) [14], grey line: England (EN) [15], Dashed grey: Japan Tokyo [16, 17] (TH heated, TC cooled), Black line: Saudi Arabia, Dammam (D) [18], Black dash: European offices {EU] [6]. (Figure Nicol)

Figure 4 shows temperature clouds from surveys in different parts of the world. Part of the information collected in the surveys was whether the building was free-running or being conditioned at the time the subjects were interviewed. The method of data collection for each of the sets of data can be found in the references given in the caption for the figure. Heating is likely to be turned on when the mean outdoor temperature falls below about 10^{o}C and cooling when it exceeds 20-25^{o}C.

The clouds in figure 4 are quite different from each other in shape and placement on the graph. The clouds from China (H, B, and S), England (EN) and Russia (K) are from surveys exclusively in the winter season when the outdoor temperatures are low, and the heated indoor air can be quite warm. The outdoor temperature changes less when the data are collected in a single season rather than throughout the year (e.g. EU). There are two clouds from Tokyo which are from dwellings in the summer when cooling was on (TC) and winter when the heating was on (TH). From offices in Europe (EU) the temperature remains within a narrow band as shown in Figure 3. Dammam (D) in Saudi Arabia the cooling is on almost continuously, but the measurements were from dwellings, so a wide range of indoor temperatures follows from the different subjects. Notice that temperatures in the conditioned buildings shown in figure 4 generally fall between 10°C and 30°C.

Although in conditioned buildings the indoor temperature is effectively decoupled from the outdoor temperature by the temperature conditioning, there is clearly a noticeable effect of the outdoor temperature on that indoors. As suggested by Humphreys [8] in Figure 1 there is generally a minimum indoor temperature at outdoor temperatures around zero Celsius. The adaptive approach would predict that the lowest indoor temperatures will occur when the outdoor temperature is close to the temperature at which the occupants begin to use mechanical heating. Researchers from China [13] found that among the three Chinese cities, in winter, the lowest indoor temperature was when the outdoor temperature was around 0-10°C (S, TH and E) Higher indoor temperatures were found when the outdoor temperature fell well, below Zero (K, H and B) or rose above it (TC and D).

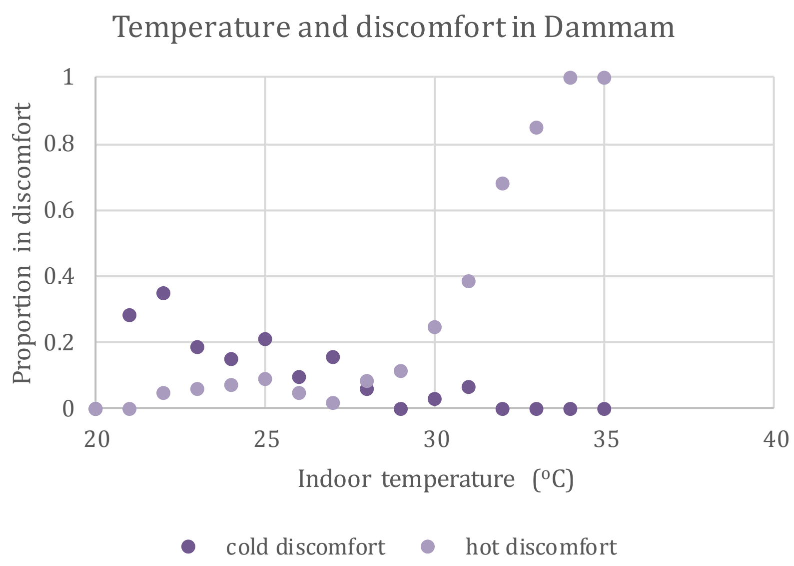

Figure 5. Proportion of occupants in discomfort from cold and heat at different indoor temperatures (°C) in dwellings in Dammam, Saudi Arabia (data from [18])

Relatively few indoor temperatures above 30°C were recorded in Dammam and the graph of discomfort given in Figure 5 suggests that heat discomfort becomes widespread (>20%) at indoor temperatures above 30°C. These are air-conditioned buildings and the comfort limit of 30°C may be lower than it could be because the occupants have expectations which are affecting their subjective response to the building. Figure 5 suggests that there is also increasing cold discomfort in this climate when indoor temperatures fall below 25°C.

3. Temperature clouds in free running buildings

Temperature clouds from free running buildings in a variety of climates are shown in Figure 6. The indoor temperatures run from below 10°C to over 35°C and outdoor temperatures from less than 0°C up to almost 40°C. The data from English (E) and Russian (M, Moscow) dwellings are from the summer and the Nepal (N) data from winter but results from Pakistan, (P) and Tokyo (T) come from data gathered throughout the year. Data from Australia was collected throughout the year but in two distinct climate zones, Melbourne (M) in the south and relatively cool and Darwin (D) in the tropical North. The comfort cloud for Shanghai (S) is also in figure 4 because many buildings in that city have no mechanical conditioning system even in the cooler season. This means they often wear thicker clothing then is common. Buildings from the UK and Moscow are assumed to be free-running in summer and seem to follow the general pattern of other buildings in this free-running group.

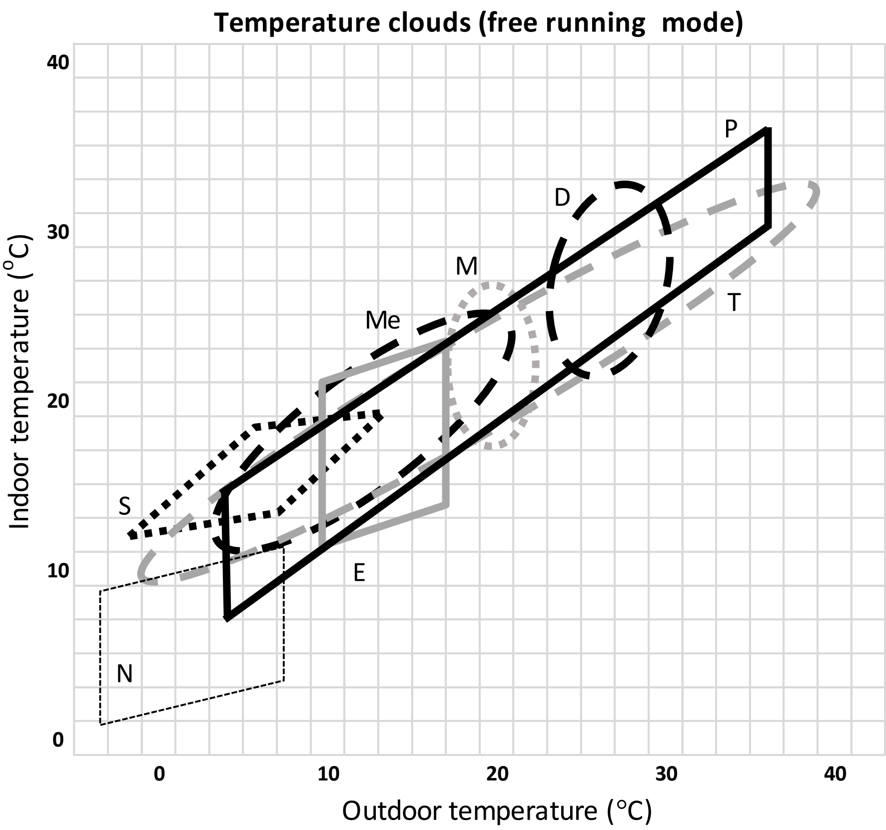

Figure 6. Temperature clouds from various parts of the world from buildings which were free running at the time of the survey. Key: dotted black: China (Shanghai)(s) [13], dotted grey - Russia (Moscow (M) summer [14]), grey line (England, summer (E) [15]),dashed grey: japan (Tokyo (T) [16, 17]), Dashed black: Australia (Melbourne (M), Darwin (D) [19]), black Pakistan (P) [20]). Narrow black dashed Nepal (N) [16]. (Figure Nicol)

Surveys in Mustang district, Nepal (N) [16] have found wintertime indoor temperatures below this, some as low as 0°C. To deal with these conditions, subjects live communally in rooms where the only heating is from small stoves used principally for cooking. Fuel for the stoves is scarce. The dwellings have small windows and thick walls to reduce heat loss and subjects wear thick clothing. These buildings are difficult to classify and have therefore been included in the free running clouds shown in Figure 6 (21) as their use of energy for heating is minimal.

Unlike the sets of data from the conditioned buildings where the clouds are separated and of a distinct shape, in free-running buildings there is a great deal of overlap between records from one country and another. The indoor conditions in different buildings at any particular outdoor temperature are likely to be caused by the physics of the building construction and layout. The inhabitants of a building will be familiar with the way their building works and will adapt the indoor conditions to suit their lifestyle and expectations. There will be differences between countries in building style clothing and culture, but Figure 6 suggests that these are less important overall than the form and physics of the buildings.

3.1 Characteristics of clouds from free-running buildings

(a) Pakistan

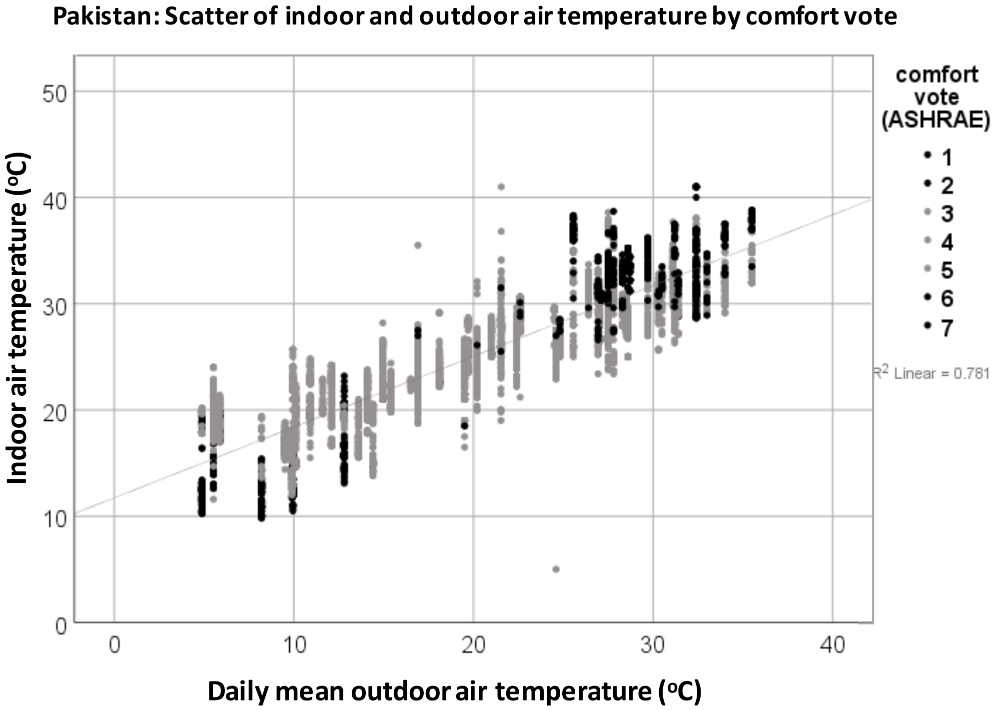

Figure 7. Comfort votes among the Pakistan data. The markers in black denote discomfort, those in grey denote comfort. Notice that heat discomfort occurs above about 30°C and above 35°C from most of the dataset [Nicol et al. 1999]. Cold discomfort occurs at 15°C and below. The highest outdoor temperatures (Tout > 32°C are from Multan, the coldest (Tout < 8°C) from Quetta. (Figure Nicol)

Figure 7 shows the temperature cloud for the Pakistani data collected in 1995-6 [20] from five widely cities of the country (Saidu Sharif, Islamabad, Quetta, Multan and Karachi) at all times of year. The position of each point shows the indoor temperature and the daily mean of the outdoor temperatures from local weather stations. The use of the daily mean instead of the instantaneous temperature explains the vertical striations in the cloud and means that the range of outdoor temperature will be reduced somewhat. Black points indicate discomfort and grey points comfort (votes 3, 4 and 5 on the ASHRAE scale) Throughout the year and in the different parts of country the subjects are comfortable except when the indoor temperature is less than about 15°C or above about 30°C where subjects become increasingly subject to discomfort.

(b) Portugal

Figure 8 presents the temperature cloud from European SCATs surveys in three Portuguese offices in Lisbon and Porto [6]. Records from the three medium/heavyweight 20th century office buildings (P2, P3 and P5) are separately identified in the Figure 8. These buildings were naturally ventilated and in a free running mode for most of the time so there will be no mechanical ventilation to create a difference between the outdoor and the indoor temperatures. The shape of the resulting temperature cloud reflects the relationship between the indoor and the outdoor temperatures. These are well correlated, and this gives rise to a cloud with a 'slanting cigar' shape, the indoor temperatures reflects a passive response to the outdoor temperature. Each building has a different cloud, but the overlap includes all three. The regression coefficient between the two temperatures is 0.43 with a coefficient of determination, R^2 = 0.62 suggesting that more than 60% of the variance of indoor temperature is associated with that of the outdoor temperature. The value of these statistics are closely mirrored by those of the individual buildings (Table 2) despite clear differences in the clouds.

Table 2. Results of separate statistical analysis of NV Portuguese buildings. The number of subjects the mean and range of indoor temperature are shown for each building as well as the calculated regression slope, and intercept and index of concordance (R^2)

Buildings	N	R^2	Regression slope	Intercept	Comfort (%)	T max (°C)	T min (°C)	T mean (°C)
P2 Porto	140	0.67	0.45	15.8	89	28.6	18.7	23.4
P3 Lisbon	136	0.45	0.47	15.8	91	29.3	19.7	23.9
P5 Lisbon	248	0.77	0.43	15.4	87	29.2	18.9	23.1
All	524	0.62	0.43	15.9	89	29.3	18.7	23.4

Each of the 500+ points in Figure 6 represents one estimation of the physical environment, the subjective comfort vote and other responses from one of the subjects at a particular time. This means that for each point, the value of the comfort vote or other variables (such as the use of adaptive opportunities - windows, blinds, clothing use etc.) will have been recorded, and can be identified in the cloud. This can help to find the ways in which adaptation has occurred, two examples are shown in figure 9.

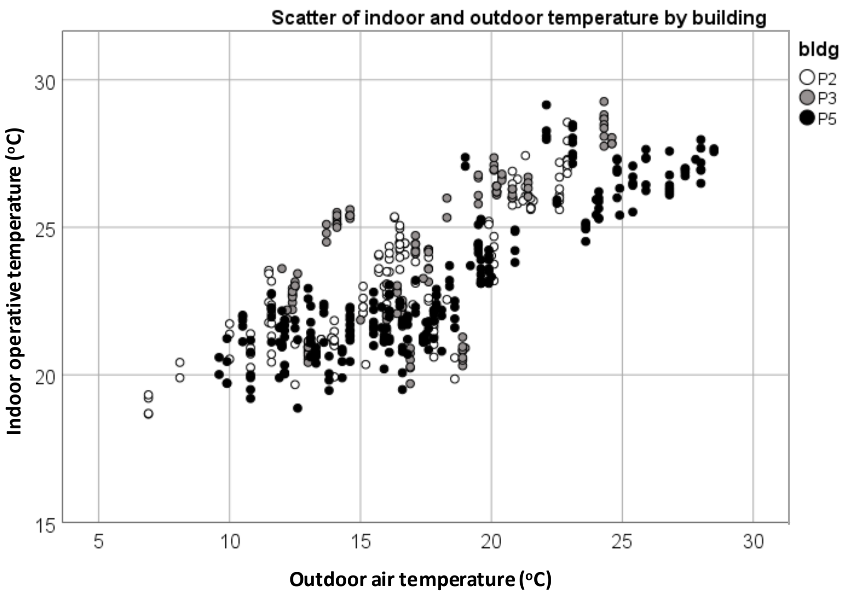

Figure 8 Cloud of data from three naturally ventilated offices in Portugal, data from the SCATs project [6], surveys conducted over a year in the period June 1998-September 1999 (Figure Nicol)

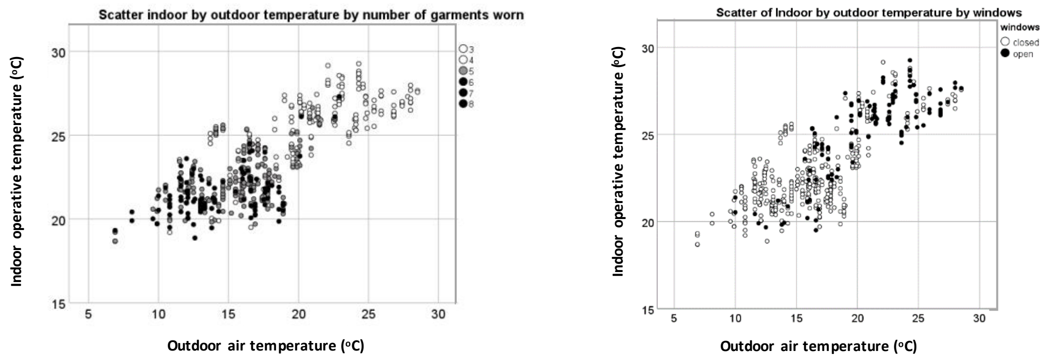

Figure 9. Demonstrating the ways in which the number of items of clothing worn (left) and open windows (right) are used as part of the adaptive mechanism. Data from SCATs surveys in Portugal. 88% are comfortable. Figures: Nicol)

3.2 Relationship between indoor and outdoor air temperature in some Tokyo dwellings

The temperature cloud can also help to understand some data collected by Rijal et al. [17]. These data were collected in Tokyo from Japanese subjects in their free running homes. The resulting temperature cloud is shown on the left hand of Figure 10. From the shape of the cloud it appears that some measurements are made in heated or cooled rooms (roughly those within the grey ellipse) and but these appear to have been included in the free running cloud. The dashed oval shape in the right-hand figure represents the likely shape of the cloud with the heated and cooled points excluded. This data might lead to misinterpretation of the dataset. Taken together the presence of the points from the rooms which appear to be mechanically conditioned could be taken as a reduction of the slope of the regression line.

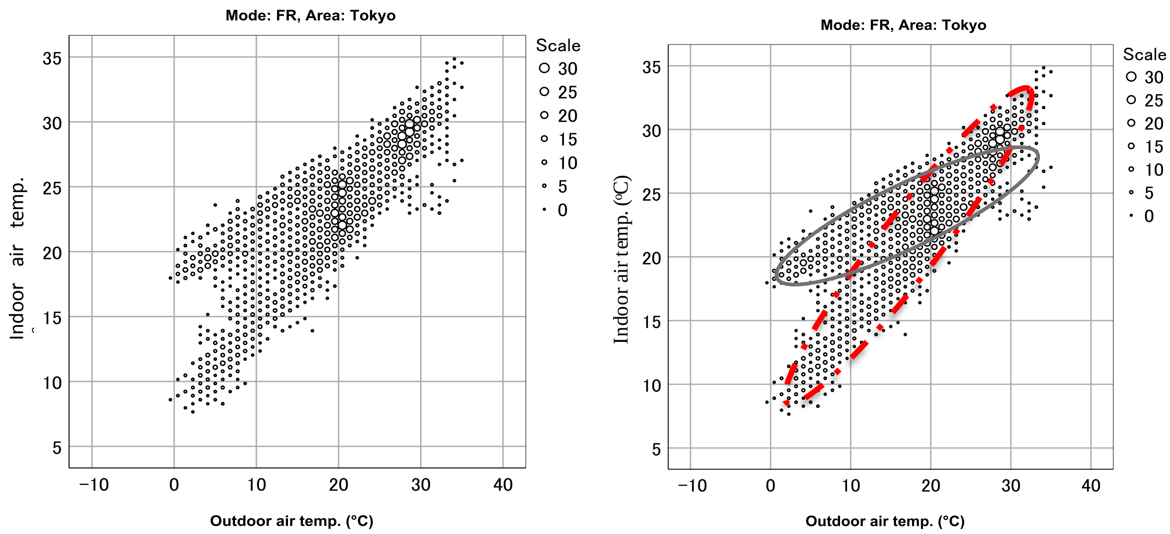

Figure 10. Plots of the indoor temperature and the concurrent outdoor temperature in dwellings in Tokyo. These data were collected year-round in buildings where the rooms were recorded as being free running at

the time of the survey. The suggested 'cigar shaped' cloud (free running) is shown on the right-hand image by the dashed line. The grey line suggests a possible area of a mixture of free-running and heating.

3.2.1 Analysis of the information

The data used in this analysis is obtained from field surveys conducted during 4 years in dwellings in the Kanto area of Japan [12, 22, 23 24]. The field survey was conducted in five different periods. The data was collected from living rooms and bedrooms.

Having analysed the relationship between indoor air temperature and outdoor air temperature in buildings during "Free running (FR)" in the Tokyo area, it was found that when the outdoor air temperature is low, the indoor air temperature distribution falls in two groups. In order to clarify this difference, we have extracted two dwellings for comparison of indoor air temperature. The following analysis was made to find an explanation for Figure 11.

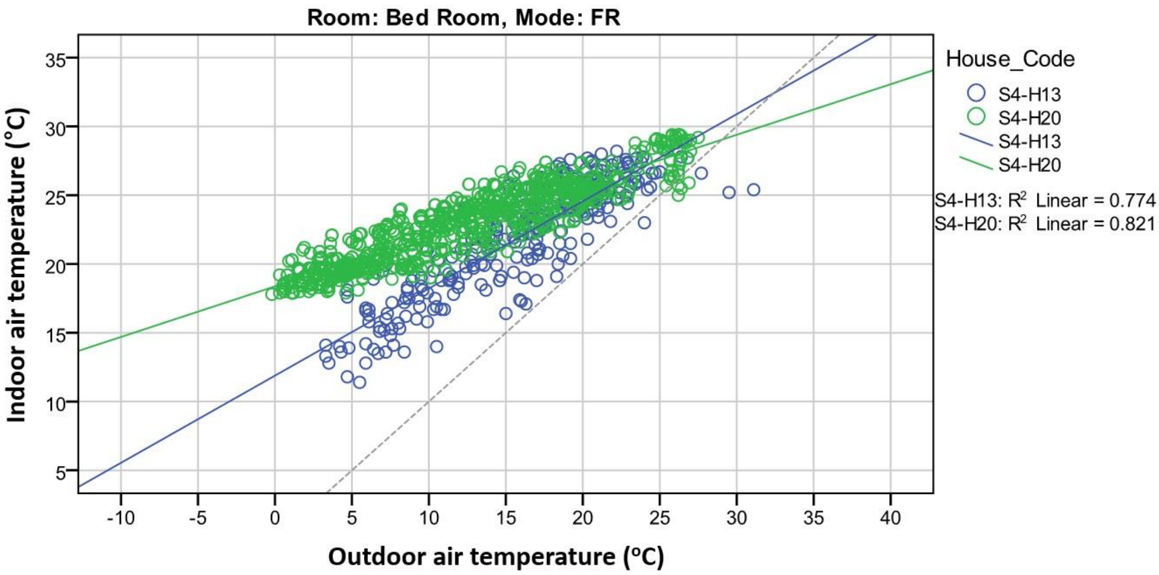

Figure 11 Showing the indoor temperatures in dwelling S4-H20 (grey) compared to that in S4-H13 (black). Note that at low outdoor temperatures the difference between the two is greater

The bedroom of "S4-H20" dwelling had higher indoor air temperature than the other dwelling "S4-H13" (Green cloud in Figure 11). S4-H20 dwelling is in the "RC condominium" group. At first, we reproduced the relationship (Figure 10) between indoor and outdoor air temperature during FR mode in Tokyo.
Second, we considered whether the indoor thermal climate is dependent on the use to which the space put. We analysed to relationship between indoor and outdoor air temperature in bedrooms and living rooms. The indoor air temperature in the living room is not a 'separated' distribution but, in bedrooms is separated in two different distributions when the temperature is low (Figure 10).

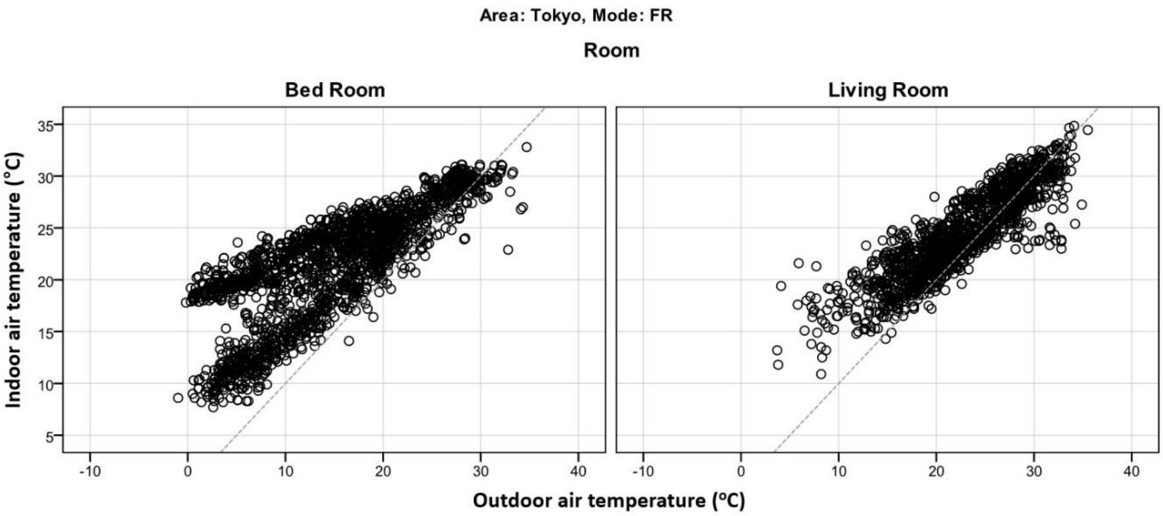

Figure 12. Temperature clouds for Bedrooms (left) and living rooms (right) in free-running Tokyo dwellings.

It is not known whether ‘separated distribution’ happens only in winter or also spring and autumn seasons. To investigate this, we analysed the relationship between indoor and outdoor air temperature in each season. It was found that the bedroom indoor air temperature in spring and autumn also has two separate distributions (Figure 13). The analysis of the ‘two distribution’ needs to include not just winter but also spring and autumn seasons.

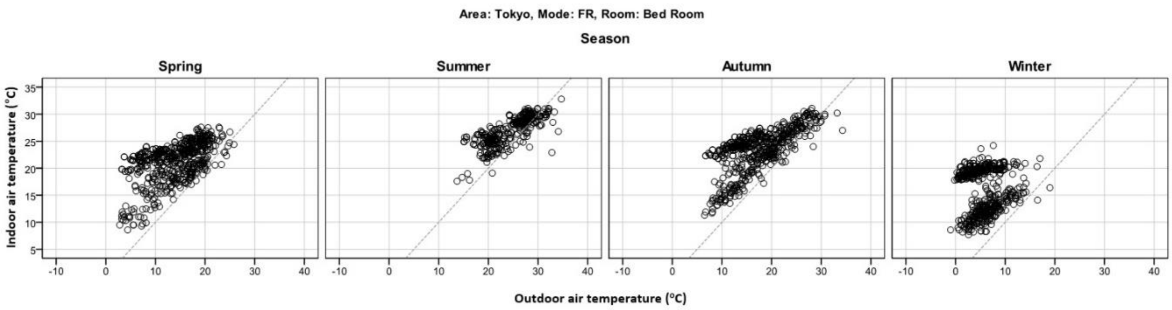

Figure 13. Seasonal variations in the comfort cloud

We thought that separated distribution is depended by difference of each dwellings. In order to find which bedroom made different temperature cloud, at first, we have analysed temperature cloud from bedroom by each survey. In survey 4, there are ‘two distributions’ stem of temperature cloud (Figure 14). And thus, we have also analysed the temperature cloud by each bedroom of survey 4 in Figure 16.

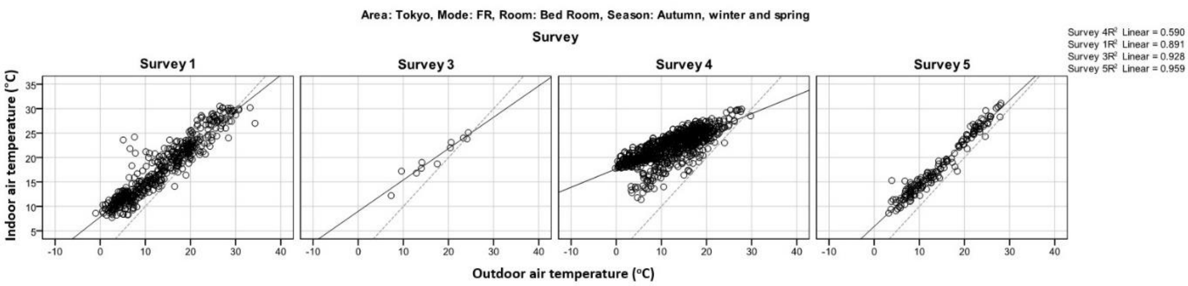

Figure 14. Temperature clouds from bedrooms in different buildings in 4 Survey. In survey 2, we did not collect the data in bedroom.

We conducted a total of 5 surveys. In Figures 12 and 13, we analyzed all 5 surveys data. Figure 14 shows an analysis for each survey without survey 2 (because survey 2 did not investigate in bedroom). This survey data was collected from many bedrooms. So, when we would like to analyse relationship by each dwelling, we want to know which survey has the separated distribution. We have analysed by data from each survey, and we know that "only survey 4 data has separate distribution". And thus, Fig 15 analyses only survey 4 data in next step. (In survey 4, there are 4 dwellings in FR mode Bedroom)
We have extracted sufficient amount of data from two dwellings . The regression slope of "S4-H20" is lower than for "S4-H13". As can be seen in Figure 15 the cloud for "S4-H20" RC condominium flat had higher indoor air temperature than the other houses when the outdoor air temperature is low. This trend is confirmed by Rijal et al. [25]

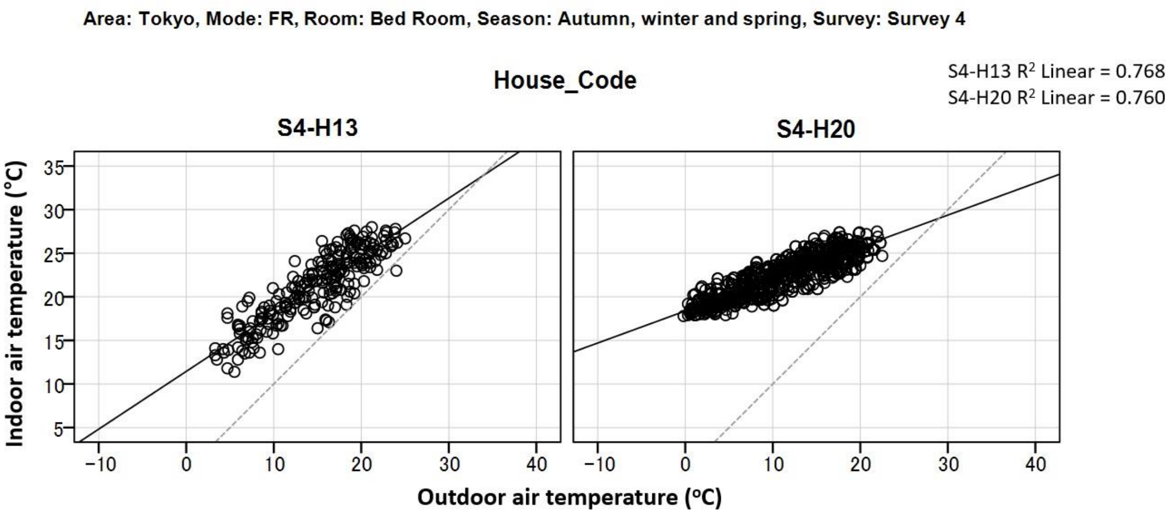

Figure 15. Showing bedroom temperature clouds for two different buildings in Survey 4

Table 3. Differences in age and construction of the buildings

Item	S4-H13	S4-H20
Type	Detached	Condominium
Building age	15-19	10-14
Structure	Wooden	RC
Floor of bedroom	2F	2F

Table 3 shows the differences in the construction and materials for buildings S4-H13 and S4-H20. The former is a wooden detached residence and the latter a concrete condominium. Bedrooms of both are on the second floor.
In S4-H20 living room and bedroom are facing "South". This flat is located in the "second floor" of the 7-story condominium. The living room and bedroom are connected by Fusuma

[4] - Japanese sliding doors which have low insulation and low airtightness.

3.2.2 Conclusions of the analysis

The bedroom temperature in S4-H20 may be high for one or more of the following reasons:

1. Although they are not using the heating in the bedroom, they are using heating in the living room and thus some of the heat goes to the bedroom through the Fusuma.
2. The bedroom faces south and receives solar radiation through big windows and the concrete wall is heated in the daytime and stores the heat. The temperature of the south facing bedrooms is higher than north facing ones.
3. The flat is located on the second floor and surrounded by other flats: not located in ground floor, corner or top floor. Thus, the insulation level would be very high, and they may also receive the heating from other flats.

The reason for the 'double slope' of the cloud from Tokyo would seem to be that the temperature in at least one of the bedrooms is running high. This is probably because they apply in particular circumstances (such as sunny days or use of heating in one part of the dwelling but not in another). This suggests that the bedroom is seen by the occupants or researchers as free running, when in fact it is being heated indirectly by the sun or appliances in next-door rooms or dwellings.

4. Comfort or survival in an emergency?

The Intergovernmental Panel on Climate Change (IPCC) expects increasing climate change to cause an increase in the frequency of extreme weather events. During these events people's concern could change from comfort to survival. Thapa et al. [21] report measurements of comfort and thermal acceptability of the thermal environment in emergency shelters built after the 2015 earthquake in Nepal. Although the extreme event was not directly weather-linked the researchers considered that asking the subjects about the acceptability of the thermal environment might provide some insight into the effect of the emergency situation.

(a) The situation of temporary shelters in Nepal

In Figure 16 the columns labelled according to season, show the percentage of acceptance using the direct question "Can you accept the present thermal environment?" to know the indoor thermal environment is acceptable to them or not. The results found that, the percentage of acceptance is 90% in autumn and it is even higher in winter and summer. Thus, the author applied the indirect method for the estimation of the thermal acceptability of respondents define by conventional ASHRAE criterion votes 3-5 (Conventional Thermally Acceptable Zone, CAZ) as being 'comfortable. The wider criterion of votes 2-6 (Wider Thermally Acceptable Zone, WAZ) being acceptable is shown to give a higher proportion of acceptable. As we discussed, considering only a direct vote of 'acceptable' thermal acceptance was higher than 90%. The wider comfort zone (2-6 rather than 3-5) does increase the level of acceptance, but not so much as the direct question.

Thapa et al. [21] suggest that the high acceptance to the direct question can be attributed to "either 1) The respondents admitted the given conditions and were feeling rather lucky that they have been able to survive from the disaster, for which nearly 9000 people were killed or 2) The basic needs are food, clothing, sanitation and a place to live for

[4] https://en.wikipedia.org/wiki/Fusuma

resting rather than thermal acceptance. It means that they gave the first priority for their survival and safety and the second for comfort and health.”

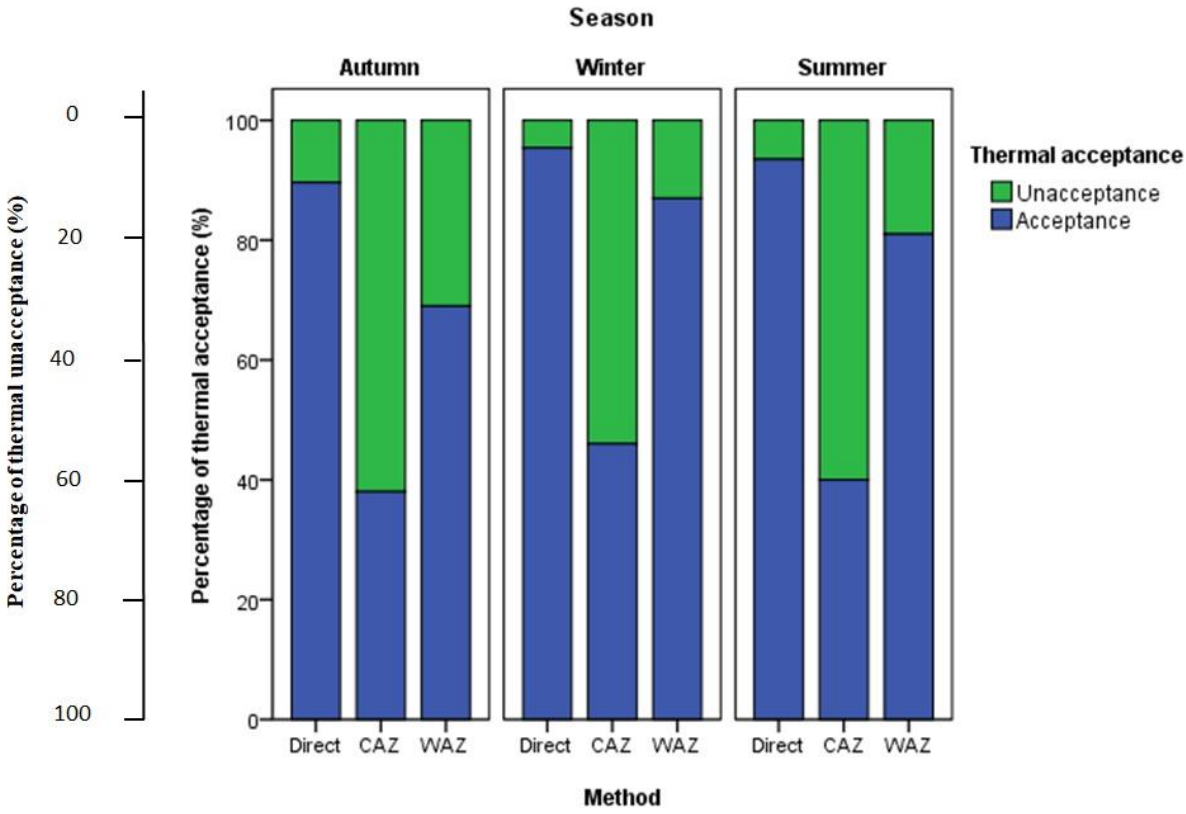

Figure16. Comparison of the percentages of thermal acceptance according to the range of acceptability (from [21])

This study suggests that ‘comfort’ as defined by ASHRAE [9] after Fanger [4] as votes of 3, 4 or 5 on the ASHRAE scale may be too narrow to define acceptability in emergency situations. Researchers asking subjects who were victims of the 2015 earthquake found that environments which gave votes between 2 and 6 could be considered acceptable in these circumstances.

(b) The situation of Japanese house

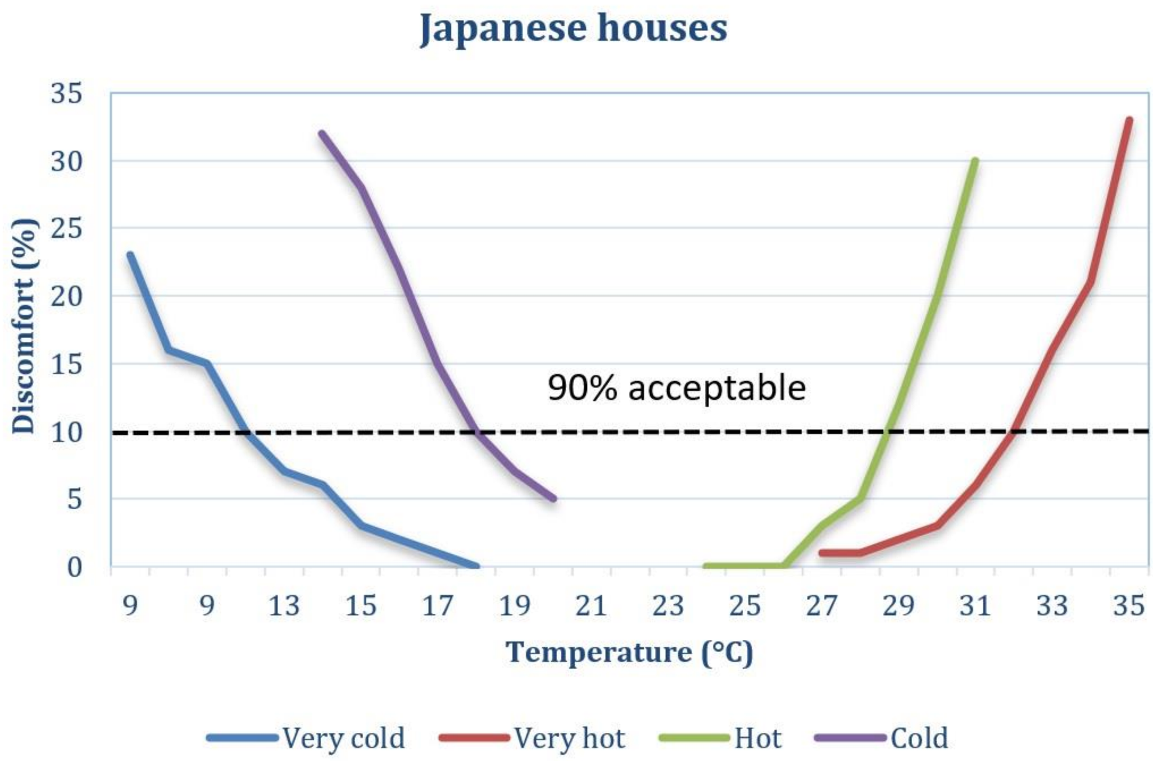

Figure 17 The effect on the percent acceptable when the acceptable range for the SHASE vote (1. Very cold, 2. Cold, 3. Slightly cold, 4. Neutral, 5. Slightly hot, 6. Hot, 7. Very hot) is increased from votes 3-5 (hot/cold) to 2-6 (very hot/very cold). The horizontal line denotes 10% discomfort (Figure Nicol)

Comparing this to data from Japanese homes this means that whereas in normal times the temperature range for 90% acceptable is 17-29^{o}C in emergency situations this range may widen to 11-32^{o}C. (see Figure 18), or beyond. Figure 17 shows the effect on the percentage of thermal acceptability of changing the width of the ASHRAE/SHASE [5] comfort zone at different indoor temperatures in Japanese houses. The two upper curves take discomfort as being defined by votes 1 and 2 (cold) and 6 and 7 (hot). Japanese [1] and Pakistani [20] occupants of free-running office buildings are comfortable. 86% of Japanese and 78% of Pakistani subjects responded with votes of 3, 4 or 5 with the remainder about equally divided between hot and cold discomfort.

5. Conclusions

Overall the early work of Humphreys [8] and Figure 1 is supported in two ways: firstly, the general shape of the relationship between indoor and outdoor temperature is curvilinear in buildings with mechanical conditioning. The indoor temperature tends to increase as the outdoor temperature becomes either lower or higher than about 0-10^{o}C (Figure 4). Secondly in free-running buildings there is an almost linear relationship between indoor and

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[5] The wording of the SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan) comfort scale is similar to that ASHRAE scale (see caption to Figure 18) but changes the wording to use the words 'cold' and 'hot', rather than 'cool' and 'warm' which have no equivalent in Japanese language. For the full wording of the questionnaire see Rijal et al [2019]

outdoor temperature and the relationship between the two is similar in a wide range of climates (Figure 6).

Using temperature clouds allows observation of the dispersion of temperatures inside buildings and to observe the full range of temperatures found and their relation to comfort (Figure 7). It also supplies a method by which to observe how measured adaptative behaviour can be evaluated. Temperature clouds can also suggest new ways to approach the evidence from a database which might be missed by an approach which assumes accepted relationships or distribution of comfort data (Figure 10).

The maximum indoor temperature for acclimatised building occupants, as suggested by the temperature clouds illustrated in this paper, is 30-35^{o}C. The minimum indoor temperature acceptable to appropriately acclimatised subjects is 10^{o}C. The data from Nepal [Rijal 2019] suggests that appropriately adapted subjects can find even lower temperatures comfortable in extreme circumstances. Roughly the same temperature limits apply in both conditioned and free-running buildings.

Whilst most of the temperature clouds in Figures 4 and 6 pass at some time through the indoor temperature range 20-25^{o}C, this may not always be the case. Most of them spend long periods of time outside this narrow range, especially if there is a large seasonal temperature range. So it should not be taken as given that the 20-25^{o}C is necessarily the temperature range to aim for. At some times of year, or in particular buildings, it may be found uncomfortable. In addition, it is generally accepted that providing a constant indoor temperature can be costly in energy and may in some instances be unhealthy [26].

By definition, little or no energy is used for heating or cooling when a building is in free-running mode. This means that the occupants need to learn to adapt appropriately (by changes of clothing and activity or use of fans, shading etc.) to what is, in large measure, a 'given' indoor temperature.

Not all the temperatures that exist in a building are necessarily comfortable to all occupants, but analysis such as that presented on Figure 7 and [1] suggests that comfort is possible at most temperatures in that environment.

Comfort clouds are particularly useful in suggesting analyses such as that of Figure 10 where without an anomaly which arises from the shape of an assumption of there being a single regression would have neglected an interesting and important difference between buildings included in a survey. Rijal et al. [25] conducted an extensive literature review and confirmed that significant amount of energy can be saved by natural ventilation and adaptive model.

90% of survivors from the Nepalese earthquake disaster accepted the indoor thermal environment in temporary shelters. This suggests that an indoor climate is acceptable if the subjective vote is in the range 2-6 rather than the recognised range of 3-5 [9]. This implies that the globe temperature should be higher than 11 ^{o}C in winter and lower than 30 ^{o}C in summer [21].

Further work is necessary to explore the comfort clouds approach to temperatures in buildings. In particular, in developing methods to define more precisely the limits of particular clouds, and the interpretation of the different shapes they take.

6. Acknowledgements

Thanks are due to the various people who have collected or taken part in the surveys quoted in this paper. It is clear that the approach discussed needs a lot more work but even at this level it yields some interesting insights for the future.

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