Outdoor Thermal Comfort

A Model Based on Thermal Adaptation in New Zealand

Kasun Perera¹, Michael Donn², Marc Aurel Schnabel³
¹, ², ³Victoria University of Wellington, New Zealand
kkperera@gmail.com¹, {Michael.Donn², MarcAurel.Schnabel³}@vuw.ac.nz

Abstract: In the recent past outdoor thermal comfort research has moved to investigate the combined effects of sun, wind and temperature with the human adaptation aspects which had led to identifying many contradictions between the results provided by physiological models and actual thermal perceptions in real outdoor environments. These discrepancies are primarily due to human adaptation to the thermal environment. This paper reports a model developed to comprehend and test adaptation aspects involved and how it influences thermal comfort assessment based on peoples’ thermal expectations and preferences. This investigation involves the Universal Thermal Climate Index (UTCI), an advanced outdoor comfort model currently used globally to examine its applicability in the New Zealand context. The study reveals that standard physiological models cannot be directly applied to different climates to predict comfort levels for various thermal expectations.

Keywords: Outdoor thermal comfort; thermal adaptation; thermal perception and expectations; UTCI.

1. Introduction

Outdoor thermal comfort in an urban environment is a complex issue, which cannot be limited merely to temperature or windiness. However, it is one of the factors that influence outdoor activities in streets, plazas, playgrounds, urban parks, etc. The amount and the intensity of such activities are affected by the level of the discomfort experienced by the inhabitants when they are exposed to the climatic conditions in these outdoor spaces (Givoni, 2003). Peoples’ sensation of thermal comfort is affected by the local microclimate and becomes a decisive factor in the use of space. Gehl (1971) in his work, “Life between Buildings: Using public space” studied the influence of microclimate on outdoor activities by counting people sitting on sunny and shady benches. He showed that local sunny or shady conditions significantly affect the desire of people to either stay or leave.

Altering the physical conditions of public space could enhance the usability and comfort levels of outdoor space. Moreover, a better understanding of the relative influence of the climatic parameters on human comfort in different thermal environments would be highly beneficial in successfully altering the physical conditions of space.

Current models and indices of outdoor comfort follow the theory of thermal acceptance and sensation for comfort calculations based on widely used physiological models of thermoregulation in the human.
body. In the field, human aspects of comfort assessment have for many years acknowledged behavioural adaptation. For example, the well-known ‘Lawson Criteria’ of comfort in windy environments differentiate between comfort for activities that involve sitting or standing for an extended period and comfort for activities where people are briskly walking through urban space. (Lawson, 1978) In looking to examine thermal comfort, incorporating wind, sun, and temperature effects on people, it becomes necessary to survey not only the subjective rating of comfort but also to record activity-related information.

Due to the complexity of the dynamic and subjective aspects of comfort assessment, a physiological approach alone cannot reflect the behavioural or adaptive influences of people in real environments. Chen (2012) suggests a framework to capture climate knowledge and human knowledge with physical, physiological, psychological, and behavioural attributes.

Thermal comfort studies outdoors have shown an increasing interest in the adaptive approach over the past two decades. These approaches have investigated the relative influence of the weather parameters on human comfort about tolerance rather than the degree of adaptation. According to Nicol (2008), there are two main reasons for this interest. First, are uncertainties of the possibilities of transforming the experimental results obtained under controlled laboratory environments to characterise the complex conditions of real environment settings. Second, is the trend evident in many the field studies that people adapt to the prevailing climatic conditions and tend to be more tolerant of thermal condition variations than is predicted by the laboratory-based physiological models (Brager and De Dear, 1998; Nikolopolou, Baker and Steemers, 2001; Walton, Dravitzky and Donn, 2007; Nasir and Ahmad, 2012; Rajapaksha and Rathnayaka 2019). Also, Hoppe (2002) finds that people spend only ten per cent of their time outside which goes some way to suggest that if it is indeed uncomfortable, they may elect not to do so.

2. Thermal adaptation and thermal comfort

People gain greater choice outdoors but at the expense of having to tolerate whatever environment they elected to be exposed to (Walton et al, 2007). They have less control over the environmental parameters compared to indoor environmental conditions. Adaptation is likely to be the most suitable option for people to be comfortable outdoors.

Studies done by Webb (1959), Nicol (1973) and Humphreys (1975) were the first experiments which identified differences in the results obtained by subjects and theoretical models in indoor environments. As reported by many indoor thermal comfort assessment studies done in real environments using real subjects (Sharma and Ali, 1983; Busch, 1992; Matthews and Nicol, 1995; Taki, 1999, Nicol, 1999; Bouden, 2001; de Dear and Brager, 1998) using PMV, the index that was created in a controlled environment, indicated that people were not comfortable. In contradiction to the prediction by PMV, many subjects reported they were comfortable.

Similar to the differences discovered in indoor studies, discrepancies occurred between predicted comfort levels and the subjective votes in outdoor field studies (Nikolopolou, Baker and Steemers, 2001; Thorsson, 2004; Feriadi and Wong, 2004; Zhang et al., 2007; Lin et al., 2011; Ng and Cheng, 2012; Yahia and Johansson, 2013). Early outdoor thermal comfort field studies employed indoor thermal indices such as PMV for comfort assessment (Mayer and Hoppe, 1987; Hoppe and Seidl, 1991). All the above studies done in indoors and outdoors reported contradictions between the predicted comfort levels by the theoretical models and actual subjective votes for comfort levels. Thus, it is apparent that none of these short-term changes are adequately accounted for in heat balance models (Nicol, 2004). Moreover, most
importantly, the thermal steady state between the subject and the microclimate is a rare occurrence in the outdoors.


Nikolopoulou and Steemers (2003), define “adaptation” as the gradual decrease of the organisms’ response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment. In the context of thermal comfort this may involve all the processes which people go through to improve the fit between the environment and their requirements. Brager and de Dear (1998) separated the adaptive opportunity into three different processes:

- Physical adaptation (behavioral adjustment)
- Physiological adaptation (genetic adaptation or acclimatisation)
- Psychological adaptation (habitation or expectation)

Thermal sensation votes are the most prominent method of assessing human adaptation aspects in thermal comfort assessment. However, this one-dimensional psychometric tool is initially designed for indoor environments (Liu et al. 2020). Its outdoor application has many doubts in indicating precise effects of dynamic climatic parameters on thermal comfort which are substantially governed by thermal adaptation and expectations. The initial studies in the indoor environments the neutral thermal sensation (neither cold nor warm) represented the most desired temperature. However, when it comes to outdoor comfort many studies reported discrepancies between neutral thermal sensation and preferred temperature range (Huang et al. 2017; Lin, De Dear, and Hwang 2011). The one-dimensional thermal sensation scale is mainly a representation of momentary thermal perception which does not provide a good understanding of the thermal effect of the sun, wind and temperature and their dynamic effect on thermal adaptation and expectation.

In 2007, D. Walton, M. Donn and V. Dravitzky followed a different approach to develop an adaptive comfort model for Wellington (the WDD model). The model primarily focused on integrating various human adaptation aspects into thermal comfort assessment. It is mainly a multi-dimensional model that comprises of descriptive scales that explore the perceptions of climate variables and affective scales to gauge the effect of climate variables on thermal perception. The WDD model was based on the hypothesis that the majority of people have chosen to be there will “report as comfortable outdoors”. Thus, the primary question becomes – what changes have been made to be comfortable outdoors?

The WDD model formulates adaptive opportunity as an output scale to evaluate to what degree people must change their behavior or the way they use a space in order to reach the preferred thermal neutrality. To evaluate the adaptive opportunity, 33 aspects related to human thermal perception, adaptation and expectation are evaluated to form a single scale that describes the thermal effect. This study aims to extend the WDD model to comprehend the influence of physical parameters in a broader climate range.

2.2 Method

The field survey methodology of the WDD model was followed with certain modifications to extend the climate to more seasons and a more comprehensive range of temperature, sun and wind conditions. A public park in Christchurch was added into survey locations to expand the low and high temperature
range. Christchurch has lower temperatures in winter and higher temperatures in summer compared to the site of the original study – Wellington, where high wind speeds are more regular. To improve the interpretability of the model, this extended WDD model was analysed against one of the current popular outdoor comfort models: Universal Thermal Climate Index (UTCI) (Jendritzky, de Dear, and Havenith 2012).

2.3.1 Field data collection

Local wind speed, air temperature, mean radiant temperature (shaded and exposed) and relative humidity were measured. All the equipment in the main weather station were attached at 1.5m height, which provided the pedestrian level wind and temperature data.

Measured globe temperatures were converted to mean radiant temperatures using the following ASHRAE (1997) equation.

\[
MRT = \left( \frac{(GT + 273)^4}{\varepsilon D^{0.4} \cdot (GT - T_a)} \right)^{1/4} - 273
\]

where: MRT = mean radiant temperature (°C); \( \varepsilon \) = emissivity of the globe (0.95); \( D \) = diameter (0.075 m); GT = globe thermometer temperature (°C); \( T_a \) = ambient temperature (°C); \( v_a \) = air velocity (m/s).

Survey locations were selected in central Wellington and Christchurch where the public mostly gathered to have a coffee or lunch and spend time, relax, to meet people etc. The choice of location was based partly on the availability of variation of seating choices in terms of sun/wind exposure, types of surface and use of the space during the survey hours. Variation in seating spaces provides people surveyed with the option of changing the physical conditions they experience, opening the survey to a broader range of potential responses.

Field data collection of the 2007 study was done over nine months and sampling was done over 13 days. 540 questionnaire responses were obtained in this instance and the sampling was done between 11am and 3pm. In the 2017 study, sampling was done on 24 days over sixteen months (February 2016 – June 2017) in Wellington and Christchurch. Sampling was done during the same hours and 560 responses were obtained in this survey. A total of 1100 subjective responses were collected with the climate data in both field surveys.

2.3.2 Questionnaire interview

Questionnaires were handed over to participants in these locations. The participants were selected randomly, and the main prerequisite was that the participants had reached thermal equilibrium with the thermal environment. It becomes a prime aspect as reaching thermal equilibrium is vitally crucial in precisely understanding the effect of climate on comfort. 10-minute averages of climate data were calculated for the duration people were answering the questions.

Out of all 1100 participants from 2007 and 2016 study, 50.8% were female and 48.8% were male. Most of the participants were in the age category of 16-35. The intended main use of the location was one of the crucial aspects of the survey. As the survey was done between 11am and 3pm, most of the responders were out in the parks to have their lunch or to have a small break. It was evident by the numbers, as 53.3% said they were outdoors to rest or to eat/drink.
Outdoor Thermal Comfort

The structure of the questionnaire is the same as WDD study in 2007. Thermal sensation or impression was questioned through a seven-point ASHRAE (1981) scale which ranges from -3 to +3 with a neutral category in the centre. Four questions were related to the time of exposure to the thermal environment including the intended time of stay. Participants were asked to rate the appropriateness of their clothing for the weather conditions and “clo” value was determined via an item checklist that was provided. Choice of seating position is an essential aspect in this study, as participants have the control of exposing themselves to sun or wind in an open Park. Thus, apart from the questions related to the time of exposure, questions to examine the spot participants chose to sit, the reasons for the selection, rating of the spot compared to other spaces and if they would move to another spot were asked. Three items asked for their preference for warmth, wind, and sunshine.

3. Analysis

3.1 Thermal sensation – evidence for thermal adaptation.

Similar to the results in the 2007 study, the middle three categories of comfortably warm, neutral and comfortably cold received the highest number of votes with a percentage of 80.7%. It provides further evidence to the original hypothesis that most people are likely to be comfortable outdoors as they choose to do so.

3.2 Combined Adaptive Factor (CAF) – exploring human adaptation.

Combined Adaptive Factor – CAF, is the most significant scale that was developed in this research. CAF builds on the 2007 WDD and integrates all the responses into a single scale that represents the adaptation indicated by all survey responses. This representation of human adaptation is a result of a Principal Component (statistical) Analysis (PCA) – a method of Exploratory Factor Analysis. PCA identifies and isolates the possible relationships and patterns within a set of variables to reflect potential underlying theories. This reduction of dimensionality of a big set of variables, is achieved by regrouping them into a limited series of clusters based on their correlation to each other (Bartholomew, Knott, and Moustaki, 2011). The clusters are generally known as components or factors. “Rotation” of these clusters improves the interpretation of the clusters by interrelating variables to form simple structures.

The standardised scores of all the survey responses provided four prominent clusters using PCA with Promax rotation, which had an eigenvalue score of 1. Eighteen variables were loaded into these four components and these components amount to 51% of the total variance of the dataset. The PCA analysis received a Kaiser-Mayer-Olkin measure of sample adequacy score (Kaiser, 1970) of 0.81, indicating the correlations are relatively compact and PCA can generate very distinct and reliable factors (Hutcheson and Sufroniou, 1999).

Table 01 gives the variable clusters and the likely underlying theory for these clusters can be interpreted as follows:

1. Warm or cold related – peoples’ impression of the warmth and coldness of the surroundings and their thermal sensation, level of sunlight and clothing.
2. Time of exposure – the time people have been exposed to outdoor climate, the time they would like to be exposed and their estimation before getting exposed.
3. Wind level impressions – the intensity of the wind, it is the cooling effect and if they prefer to have more/less wind.
4. Preference of sun/warm – peoples’ preference for sun levels and how warm they would want to be.

Table 01: Principal Component Analysis extraction – variable clusters.

<table>
<thead>
<tr>
<th>Abbreviated versions of the questions (not in order of asking)</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warm or cold exposure of wind of sun/warm</td>
</tr>
<tr>
<td>How warm or cold your surrounding?</td>
<td>.748</td>
</tr>
<tr>
<td>Wetness of your surrounding</td>
<td>.736</td>
</tr>
<tr>
<td>Your impression of the sunlight level?</td>
<td>.712</td>
</tr>
<tr>
<td>Level of clothing</td>
<td>-.660</td>
</tr>
<tr>
<td>Impression of how warm or cold you feel?</td>
<td>.638</td>
</tr>
<tr>
<td>Today is a good day to be outdoors. Agree/Disagree?</td>
<td>.567</td>
</tr>
<tr>
<td>Before sit, how long you expected to stay?</td>
<td>.905</td>
</tr>
<tr>
<td>How much longer do you intend to stay here?</td>
<td>.748</td>
</tr>
<tr>
<td>How much longer would you like to stay here?</td>
<td>.674</td>
</tr>
<tr>
<td>How long have you been here?</td>
<td>.660</td>
</tr>
<tr>
<td>Your impression of the wind level?</td>
<td>.778</td>
</tr>
<tr>
<td>The wind is annoying today. Agree/Disagree?</td>
<td>.759</td>
</tr>
<tr>
<td>Wind strong in exposed places?</td>
<td>.692</td>
</tr>
<tr>
<td>What you usually prefer in terms of the wind?</td>
<td>.524</td>
</tr>
<tr>
<td>Your impression of the cooling effect of the wind?</td>
<td>.503</td>
</tr>
<tr>
<td>What you usually prefer in terms of sunshine?</td>
<td>.839</td>
</tr>
<tr>
<td>What you usually prefer in terms of warmth?</td>
<td>.804</td>
</tr>
<tr>
<td>When exposed to the sun it feels you?</td>
<td>.494</td>
</tr>
<tr>
<td></td>
<td>.542</td>
</tr>
</tbody>
</table>

The first and third factors directly reflect peoples’ thermal impression as measured by UTCI and PMV. The second and fourth factors determine peoples’ reactions to the other two factors. To generate a single scale that represents the entire climate variables and peoples’ impressions, these factors are combined to develop the CAF score.

The CAF score is generated by computing the weighted aggregate for each component which precisely represents the contribution of each variable to the factor. CAF scale interpretation was done by mapping CAF scores with actual subjective responses. It was identified that lower CAF scores indicated that people were feeling cold higher wind/wind chill impressions and preferred more sun and to be warm. The lower CAF scores were linked with lower exposure times as well. Higher CAF scores indicated that people felt relatively warm and preferred more wind and less sun.

The CAF score was examined to find the neutral range where people are comfortable. For this purpose, two questions were used – impression of warm or cold (a descriptive variable) and is it a good day to be outdoors (an affective variable). It should be noted that, only these two questions were used in this study to setup the framework for the multi-dimensional thermal affective CAF model. The actual comfortable range and preferred comfortable range can be more precisely understood by engaging more variables into the analysis. Figure 1 and 2 shows that people have indicated CAF range of 38.8 – 44.7 is comfortable.
3.3 Thermal Adaptation Index (TAI) – linking human adaptation to climate.

To investigate the influence of sun, wind and temperature on thermal comfort, CAF score was regressed with climatic data for all 1100 responses. The model had $R^2 = 0.40$ with a significance of $p < 0.01$. Ambient temperature, wind and wind gust seem to be the prominent predictors of adaptivity in this case.

Thermal Adaptation Index.

$$TAI = 24.53 + 0.42 \text{ (ambient Temperature)} + 0.31 \text{ (Wind Speed)} - 0.58 \text{ (Wind Gust)} + 0.05 \text{ (Relative Humidity)} + 0.15 \text{ (Mean R Temp – Exposed)} + 0.24 \text{ (Mean R Temp – Shaded)} \quad (1)$$

Wind gust has a negative effect on outdoor comfort, which is in line with what people have reported. It is reasonable to assume that RH does not have a significant impact on overall comfort levels. Both wind speed and ambient temperature have a positive impact on comfort levels, while MRT exposed has less impact than MRT shaded.

3.4 Thermal Adaptation Index (TAI) and UTCI

The TAI equation provides an understanding of the thermal effect of physical parameters in New Zealand climate. However, the neutral ranges for TAI should be identified and the stress inflictor on each extreme end need to be determined. For this purpose, two methods are used, 1. Identify and confirm the scale with CAF score. 2. Analyse the scale against UTCI to reveal and confirm the representations of comfort by TAI.

TAI score is regressed against CAF ($y = 24.6 + 0.4x, R^2 = 0.4$) and the neutral range for TAI was discovered as 39.2 (comfortably cold) to 43.08 (comfortably warm. Moreover, the neutral TAI score for this assessment was identified as 40.83.

To confirm the TAI score represents heat and cold stress accurately, it was regressed with UTCI.

UTCI is a function of ambient temperature (Ta), Relative Humidity (RH), Wind velocity (V10) and Mean Radiant Temperature (Tmrt) given in the following equation (Blazejczyk et al. 2012) and the calculation was done using the Rayman Pro software package.

$$UTCI = f (Ta; Tmrt; V10; RH) = Ta + Offset (Ta; Tmrt; V10; RH) \quad (2)$$
Mean Radiant Temperature ($T_{rnt}$) for exposed spaces that was calculated earlier has been used in UTCI calculations. Wind speed at 10m above ground level is another requirement for UTCI calculation. Since the wind speed was obtained at the pedestrian level, which is 1.5m above ground level, the power of law equation by Gandemer and Guyot (1976) was used to calculate wind speeds at 10m level.

$$\frac{\bar{U}_z}{\bar{U}_{G}} = \left(\frac{Z}{Z_G}\right)^\alpha$$

$\bar{U}_z$ = Mean wind speed at the site (m/s), $\bar{U}_{G}$ = Mean wind speed at the gradient boundary layer, $Z$ = Wind speed at 10m height, $Z_G$ = height of weather station – 1.5m, $\alpha$ = Terrain-roughness co-efficient (0.35 for small density city)

TAI and UTCI have a very significant correlation with $R^2 = 0.90$ ($y = 28.13 + 0.76$) which suggests that TAI scores can be interpreted using UTCI categories.

UTCI is expressed as “an equivalent ambient temperature (°C) of a reference environment providing the same physiological response of a reference person as the actual environment” (Blazejczyk et al. 2012). Generally, UTCI comfortable range spans from +32 to 0 °C, with the no thermal stress reported for the range from +9 to +26 °C. To clearly understand the distribution UTCI and TAI were calculated based on the as measured data collected in the 1100 survey measurements in 5 °C temperature brackets.

Figure 03 – Mean UTCI and TAI in different temperature brackets – adjusted TAI scale

UTCI and the TAI score follow the same trend confirming that low TAI scores indicate cold stress and high TAI scores indicate heat stress. However, the raw TAI score does not vary over as wide a range as UTCI, so we cannot assume that TAI produces an exact facsimile of the UTCI which calculates an equivalent air temperature representative of each combination of sun, wind and temperature.

Figure 03 shows the adjusted UTCI and TAI graph with equal neutral scores. This arbitrary scaling converts the value of the TAI score into a temperature. Since the same climate parameters are used to generate both UTCI and TAI, it is reasonable to assume the neutral or the comfortable equivalent temperature range would be somewhat similar. However, when it is colder, TAI gives a lower score than UTCI. Which means either UTCI overestimates the comfort levels in much colder thermal environments or TAI exaggerates the discomfort. It turns the other way around where UTCI predicts much greater tolerance to warmer climates than TAI. Further looking into the subjective responses on warm/cold
impression, the subject sample that was taken for this study - predominantly people in temperate climate - have reported somewhat differently than what is predicted by UTCI.

![Graph](image)

Fig 04 - Subjective response distribution for thermal perceptions – UTCI and subjective responses The physiological model has overestimated the comfort levels when it is directly compared with subjective responses. From the above figures it is evident that people are more affected by heat and cold stress in warmer and colder days than is predicted by UTCI. This model can be developed using the results from component 2 – a time of exposure to investigate the relative influence of sun, wind, and temperature on various exposure time scenarios. It could develop the model into a much more useful tool to predict preferred comfort levels for various functions and use of space. When the TAI score is calculated for people who are planning to sit outside for long or short periods, the slope of the TAI score is significantly different.

5. Discussion

People have different choices and preferences when exposed to the outdoor climate. Also, they adapt to the existing environmental conditions in order to increase comfort levels. CAF provides a much reliable indication of thermal effect and comfort over one-dimensional thermal sensation votes. In CAF, only 36.7% of the total people indicated to be comfortable, whereas subjective warm and cold impressions indicated 80.7% are comfortable. It is a significant drop of 44%.

This study has given satisfactory evidence for the fact that people do get adapted to the thermal environment and the ways they adapt is the key to assess comfort precisely.

Furthermore, it signifies the drawbacks of physiological models in predicting what people feel and prefer in outdoor environments. It points to the need for calibrating physiological models to various climates where people have different perceptions and expectations of thermal environments. A generic physiological model is insufficient for capturing the richness of local adaptation.

The adaptive model presented needs further investigation in a broader range of climates range – including hot humid, hot dry and colder climates to precisely comprehend how it could be developed to identify the unique adaptation characteristics.
References


