CLIMATE, CLOTHING AND ADAPTATION IN THE BUILT ENVIRONMENT

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ABSTRACT
Specification of acceptable indoor temperatures depends, in part, on assumptions about what people will be wearing. These assumptions have implications for optimising both thermal comfort and energy conservation. Recent proposed revisions to ASHRAE Standard 55 include an adaptive comfort standard that allows a wider range of acceptable indoor temperatures, presented as a function of outdoor weather conditions. Clothing behaviour is one of the causal linkages between indoor thermal comfort and outdoor weather. This paper quantifies this relationship using a cross-sectional study of clothing insulation patterns observed in Sydney, Australia. Fifty two percent of the day-to-day variance in mean daily clo values was accounted for by daily outdoor temperature, and no statistical association between clo values and prevailing indoor temperatures. This paper concludes with an equation for a weighted running mean weekly temperature which can be used in an adaptive algorithm for defining variable indoor comfort temperatures in air conditioned buildings.

INDEX TERMS
Clothing, Adaptation, Comfort, Set-points, Energy.

INTRODUCTION
Clothing can be looked at from a variety of perspectives. From an ergonomist's perspective clothing may (or may not) make a workplace environment safer and healthier for workers. From an anthropological perspective clothing has, along with shelter and fire, allowed our species to venture well outside the tropics (Clark and Edholm 1985). From a social angle clothing can be variously thought of as a projection of personality, mood, religious, sub-cult and other group affiliations. To the psychoanalyst clothing can be construed as a marker of mental health, a source of pleasure, paraphilia and sexual fetish. Clothing also represents a code for organisational or corporate identity, and of course it conveys socio-economic status cues. But in conventional thermal comfort theory it reduces to thermal resistance (Gagge et al. 1941; ASHRAE 1993) and its impedance to water vapour transfers (Woodcock 1962). These thermal and mass transfer properties of clothing affect sensible and latent energy exchanges between the body and its immediate environment, impacting the body's heat-balance, its thermophysiological response, and, ultimately, conscious thermal discomfort.

Adaptive comfort model proponents have built much of their hypothesis on the active use of clothing by building occupants to adapt to indoor climates that change on timescales from days to seasonal. Recent proposed revisions to ASHRAE standard 55 include an adaptive thermal comfort standard (de Dear and Brager 2001). In that adaptive standard, acceptable ranges of indoor temperatures are presented as a function of outdoor weather conditions (mean outdoor temperature) and it is this linkage of indoor thermal comfort processes to

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outdoor weather via mechanisms such as adaptive clothing behaviour that seems to be the most contentious issue in the adaptive model.

The significance of adaptive clothing behaviour is heightened by its knock-on effect to energy consumption in the built environment. For example, Newsham used a building energy simulation package to quantify the impact of different levels of clothing adaptability on HVAC energy consumption for a typical Toronto office building (Newsham 1997). Four clothing scenarios were examined: static clothing, very limited clothing adjustment, limited clothing adjustment, and variable clothing. HVAC set-points were selected in the simulations so that the Predicted Percentage Dissatisfied index (Fanger 1970) was minimised. Newsham found that total annual heating, cooling and fan energy could be reduced from the static clothing scenario by 6%, 15% and 41% for the three adjustment scenarios respectively.

The aim of this paper is to further elaborate and quantify the causal linkages between indoor comfort processes and outdoor weather - in particular, clothing behaviour of building occupants and how it is driven by seasonal and synoptic-scale weather dynamics.

METHODS
A cross-sectional study was used to investigate average clothing insulation levels across a large sample, every day, for six months in a department store located within a shopping mall in the western suburbs of Sydney Australia (latitude 34°S). Approximately every 4th adult subject to pass the observation station was unobtrusively observed and clothing insulation value rated in units of clo (1 clo = 0.155 m² K W⁻¹). The method of clo estimation was based on the garment check-list defined in ASHRAE Standard 55-92 (ASHRAE 1992). Typically there were about 45 different subjects sampled each day, providing the basis for a mean clothing insulation value on every day throughout the six-month field campaign.

Concurrent outdoor temperatures were obtained from an automated weather station less than one kilometre from the shopping mall site. Indoor temperatures were recorded with a PT100 resistance temperature device connected to a datalogger with a scan interval of ten minutes.

RESULTS
The outdoor weather observations are plotted in Figure 1. They show the expected gradual warming of air temperatures from the Austral spring into summer. The highest daily average outdoor temperature was recorded during a brief heat-wave centred on the 11th October, quite early in the Austral Spring. Other warm-to-hot spells with mean daily temperatures exceeding 25°C occurred on 14th November and again on 2nd December. After ranking the mean daily temperatures for the entire six-month duration of the study we found the 10th percentile was 12.5°C, the 90th percentile was 22.1°C, while the median (50th percentile) was 17.3°C. This mild median temperature came within half a degree of the long-term climatological mean for western Sydney suggesting that the six-month study period was typical for the region. Despite the minor seasonal contrasts in temperature for this part of the world, the day-to-day standard deviation in mean outdoor temperature of 3.8°C suggest a fairly changeable synoptic context during the six-month study.

Indoor air temperatures within the shopping mall are also plotted in Figure 1. The graph indicates a very restricted range of indoor temperatures throughout the study despite the external seasonal variability. Indoor temperatures were within a 22 to 24°C band. The observation of just three indoor temperature excursions above 25°C throughout the entire six
months, two of which fell in winter months, underscores the absence of any seasonal adaptation in the shopping mall's HVAC system.

Figure 1. Indoor and outdoor daily average temperatures.

Figure 2. Daily averaged clothing insulation values.

Overall the clothing style could best be classified as “casual.” The daily clo values plotted in Figure 2 are averaged across all subjects assessed on a given day (n = 45). Daily mean clo values trend downwards from winter through spring and into summer. Apart from the anomalously low-clo week near the start of the study, mean wintertime clothing insulation values were generally in the 0.5 - 0.9 clo range, dropping to the 0.2 - 0.5 clo range by the mid-summer (January). A cold-snap in late spring (November) saw a sudden and brief "spike" in insulation levels up from 0.5 to 0.9 clo.

Regression of daily mean clo values on daily mean indoor temperature was statistically insignificant (F = 0.77, p = 0.37, d.f. = 1, 171) with a negligible coefficient of determination (R^2=0.0045). This suggests that clothing insulation levels worn inside the department store were independent of prevailing indoor temperatures. A similar regression of mean daily clo observations on mean daily outdoor temperature produced a highly significant model (F =
188.4, p < 0.0001, d.f. 1, 171), with 52% of the day-to-day variance in mean daily clo values being accounted for by the relationship with daily outdoor temperature.

\[ y = 0.6521 e^{-0.3509x} \]

\[ R^2 = 0.96 \]

**Figure 3.** Coefficients of determination \( R^2 \) for the relationship between mean daily indoor clothing insulation in the shopping mall study and indoor/outdoor average temperatures across various time-lags (from zero to seven days). The statistical association between daily mean clo values and outdoor temperatures was not confined to today's temperatures alone. Lagged product-moment correlations were calculated between daily mean clo on \( \text{day}_x \) and daily mean outdoor temperatures on \( \text{day}_{x-1}, \text{day}_{x-2}, \ldots \text{day}_{x-7} \). A gradual decay in correlation between \( \text{day}_x \) clo and outdoor temperature is evident as the time-lag increases from zero to seven days in Figure 3. An exponential regression model fitted to the series of eight \( R^2 \) values was able to explain 96% of the variance. In contrast there was no apparent relationship, statistical or otherwise, between daily mean clo values and indoor temperatures, regardless of time-lag (Figure 3). It should be noted that these daily temperature observations are serially autocorrelated \( R^2=0.45 \).

**DISCUSSION**

Chapter eight of the ASHRAE Handbook of Fundamentals (ASHRAE 1993) indicates that checklist estimates of ensemble clo values have errors of the order of \( \pm 25\% \) of the benchmark thermal manikin derived values. While there would inevitably be errors in the raw data collected in this project, we believe that they were randomly distributed throughout the samples. In a colder climate zone than Sydney's, the potential for underestimating ensemble clo values due to hidden garments or clothing layers might become significant. However, in Sydney's mild climate such underestimation is unlikely to be large.

Indoor temperatures prevailing in the shopping mall study had no statistical association with clo levels being worn inside the mall. This can be explained, in part, by the minimal day-to-day variance in indoor temperatures during the six-month study. In contrast, even a cursory visual analysis of the indoor clothing and outdoor weather time-series indicate a significant relationship. There were obvious variations in daily average clo values of about 0.2-0.3 clo amplitude in Figure 2, with a periodicity spanning a couple of days - apparently mirroring synoptic-scale variations in the outdoor temperature trace in Figure 1.

According to conventional comfort theory (Fanger 1970), one might expect the *indoor* rather than outdoor temperatures to be more closely correlated with *indoor* clo levels. That is,
indoor climate ⇒ body heat balance ⇒ physiology ⇒ thermal discomfort ⇒ behavioural thermoregulation (clothing). But the evidence presented in this paper demonstrates that outdoor temperatures strongly influence clothing levels worn indoors. This begs the question of how outdoor temperatures exert their effect? The answer may relate to when clothing decisions are made. The process of getting dressed in the morning involves many decisions about garment selection and overall ensemble thermal properties, and we expect that these decisions are informed, in part, by what we forecast today's outdoor temperatures to be, our memory of what they were like yesterday, the day before that, and so on.

The adaptive thermal comfort standard (ACS) described in detail elsewhere (de Dear and Brager 2001) prescribes comfortable and permissible indoor temperatures on the basis of concurrent outdoor weather conditions. The key independent variable in the adaptive model underpinning ACS is outdoor temperature. The question of what is the optimal timeframe for the mean outdoor temperature term \( T_{\text{out}} \) was not thoroughly addressed in that project - instead it adopted a pragmatic solution of one month because published climatologies are typically based on that timeframe. Nevertheless, when better weather data are available, a more accurate timescale is probably considerably shorter than a month (Nicol et al. 1995). The findings in the present field study of clothing behaviour provide some guidance as to what the optimal integration period might be. In particular, Figure 3 provides an empirical basis for defining the optimal outdoor temperature driver for adaptive comfort models. In our opinion, the ideal outdoor temperature function is an exponentially-weighted running mean spanning the last seven days (ignoring today). The weighting for our proposed \( T_{\text{out}} \) was based on the integral of the exponential function plotted in Figure 3 (see Eq.1).

\[
T_{\text{out}} = 0.34T_{(\text{day} - 1)} + 0.23T_{(\text{day} - 2)} + 0.16T_{(\text{day} - 3)} + 0.11T_{(\text{day} - 4)} + 0.08T_{(\text{day} - 5)} + 0.05T_{(\text{day} - 6)} + 0.04T_{(\text{day} - 7)} \quad ^\circ C \tag{1}
\]

\( T_{\text{out}} \) in Eq 1 can be used as input to an appropriate indoor temperature algorithm developed exclusively from air-conditioned buildings, such as the one from de Dear and Brager's RP-884 study (de Dear and Brager 1998):

\[
\text{Comfort Temperature} = 22.6 + 0.04T_{\text{out}} \quad ^\circ C \tag{2}
\]

Together, Eqs 1 and 2 allow an air-conditioned building to have a variable indoor set-point that could potentially change daily, programmed on the basis of a running-mean outdoor temperature. The resulting variable indoor climate will accommodate dynamic clothing behaviour, enhance subjective states of thermal comfort (minimising PPD), and conserve HVAC energy at the same time.

It should be noted, however, that the algorithm for \( T_{\text{out}} \) proposed in Eq. 1 is only relevant to the context where the data came from - namely Sydney Australia. The most comparable study was conducted by Humphreys in which he observed clothing levels of UK school children, visitors to a UK zoo, and also a shopping mall (Humphreys 1979). Humphreys estimated the half-life of day-to-day clothing in the UK was about 20 hours, about half the value found in the present Sydney study (see Figure 3). This is probably consistent with popular perceptions of the weather differences between Sydney and the UK.

We recognise that the utility of an exponential running mean \( T_{\text{out}} \) for use in adaptive models is going to be limited to applications where real-time weather observations are available, typically from an automatic weather station on the same site as the building in question. Another limitation of the present study's data is that they were collected from short-term
visitors to a shopping mall. It is expected that the relative significance of indoor versus outdoor temperatures on clothing behaviour will be strongly influenced by the relative duration of exposure to both environments.

CONCLUSIONS
This paper presents results from a cross sectional study of the relationship between indoor and outdoor weather and clothing insulation levels worn by adults in a shopping mall in Sydney, Australia. Approximately 45 different subjects were sampled every day for six months, providing the basis for calculating a mean daily clothing insulation value. During the six months, outdoor temperatures generally ranged between 12.5°C (10th percentile) and 22.1°C (90th percentile). In comparison, the shopping mall’s HVAC system maintained indoor temperatures between 22-24°C. Mean clothing insulation values were generally in the 0.5-0.9 clo range in the winter (August), dropping to the 0.2-0.5 clo range by mid-summer (January).

Results lend support to the adaptive hypothesis by offering compelling evidence that outdoor temperatures significantly influence clothing levels worn inside the department store, with 52% of the day-to-day variance in mean daily clo values being accounted for by daily outdoor temperature. We also found that temperatures on days prior to the study date also correlated with clothing insulation levels, suggesting some "weather memory" effect.

The present results provide a rational basis for variable HVAC set-point temperatures that reflect clothing responses to outdoor weather and seasonal dynamics. Such variable HVAC set-points will optimise comfort and conserve energy. Although the exact statistical model presented here is relevant only to the context where the data came from, we believe that the fundamental link between indoor clothing patterns and outdoor climate will be inherent in other climates and building contexts as well, and that our method can be used as a model for determining similar statistical relationships from suitable data collected in other contexts.

REFERENCES