Title
Thermal comfort in air conditioned office buildings in the tropics

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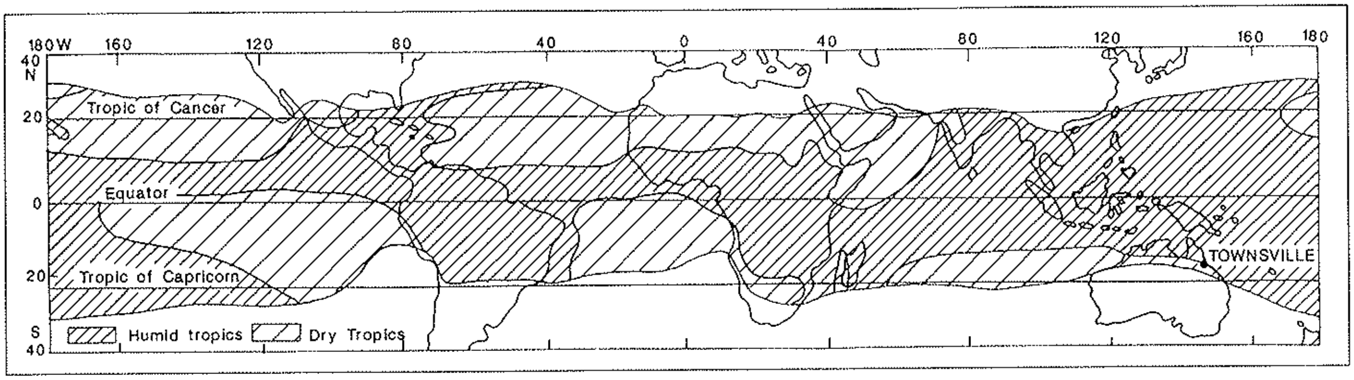
Thermal comfort in air conditioned office buildings in the tropics*

By Richard J. de Dear, Ph.D. and Marc E. Fountain, Ph.D.**



The main purpose of this paper is to summarise the key findings of ASHRAE research project RP-702, a field investigation of indoor climates and occupant comfort in 12 air conditioned office buildings in Townsville, located in Australia's tropical north. The project replicates an earlier ASHRAE investigation in San Francisco (RP-462), the main purpose being to field-validate the ASHRAE comfort chart (Standard 55) in a tropical setting.

A total of 836 subjects provided 1234 sets of questionnaire responses, each being accompanied by a full set of physical indoor climatic measurements from laboratory-grade instrumentation. In addition to the physical measurements were detailed estimates of each building occupant's metabolism and clothing insulation.

The physical environmental results are compared with ASHRAE Standard 55-1992 prescriptions and the subjective data on thermal acceptability are compared with laboratory-based comfort models and standards. Gender and seasonal effects were minor and many of the differences from the earlier San Francisco results were explicable in terms of clothing patterns. Most of the thermal dissatisfaction expressed within Standard 55's comfort zone in Townsville office buildings was associated with requests for higher air velocities.

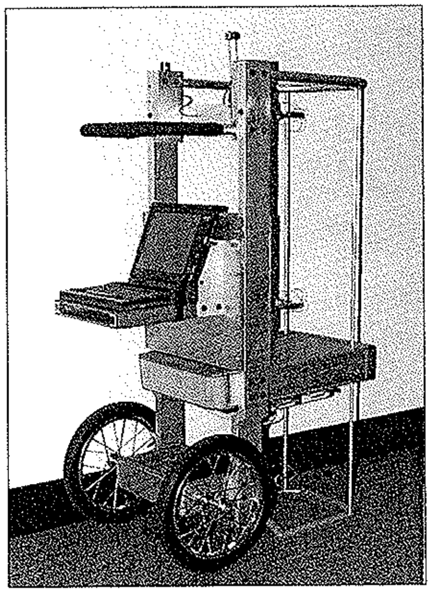


Figure 1 top : Map of the tropical world indicating Townsville's location (after Nieuwolt 1977)
Figure 2 above: The mobile measurement "Cart Mark II" used for indoor climatic data acquisition.

Introduction

ANSI/ASHRAE Standard 55-1992 - *Thermal environmental conditions for human occupancy* is based almost exclusively on data from climate chamber experiments performed in mid-latitude climatic regions (ASHRAE, 1992; 1993).

This raises two important questions when the standard is applied by HVAC engineers to populations living in other types of climates.

First, there is the lingering doubt in the minds of practising engineers about just how relevant the findings of laboratory research on university students are to "real" people actually at work in the office environment (e.g. Rohles 1978; McIntyre 1982; Prins 1992). This can be referred to as the "external validity" question.

Secondly, different climatic regions such as the tropics may call for different levels of the comfort parameters mandated in the standard, yet despite this concern, ANSI/ASHRAE Standard 55 is applied uncritically worldwide. For convenience, this second methodological concern will be referred to as the "climatic adaptation" issue.

In answer to the external validity concern, thermal comfort researchers have, over the years, attempted to validate climate-chamber results in field studies where large samples of office building occupants are invited to rate their indoor climates while the latter are measured for ambient air temperature, humidity, air motion and radiant loads (e.g. Fishman and Pimbert, 1979; de Dear and Auliciems, 1985).

The most detailed such study to date has been the ASHRAE-sponsored (RP-462) field experiment in San Francisco (Schiller et al. 1988; 1990) in which workers in ten office buildings were questioned about their workstation's immediate environments which were simultaneously being measured by a customised cart carrying laboratory-grade indoor climatic instrumentation (Benton et al., 1990).

While neutrality of the field sample was

**Results of Cooperative Research (RP-702) between the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., and Macquarie Park Research, Ltd.*

predicted quite well by the laboratory models and standards, several assumptions within contemporary thermal comfort theory were not well supported (see Schiller et al. 1988; 1990; Brager et al. 1994).

Because the San Francisco field validation study was carried out in only one climatic region (Mediterranean), it cannot sustain generalisation to the comfort responses of building occupants acclimatised to more extreme climates than those found in the San Francisco Bay Area. Review papers of thermal comfort field studies by Humphreys (1981), Auliciems (1983) and de Dear (1994) have all demonstrated a significant positive correlation between indoor comfort temperatures and levels of warmth prevailing in the outdoor climate. However, in most cases the field data upon which these correlations were based came from instrumentation and measurement protocols of a lower grade than those used in the San Francisco experiment, thus preventing unequivocal conclusions from being drawn.

Many countries in the tropical world (see Figure 1), particularly in hot-humid Southeast Asia, are undergoing rapid economic development at the present time. Despite a prolonged global recession in the early 90s, the aggregate economy of Southeast Asia still managed to grow by 5.8 per cent in 1992, including 8 per cent GDP growth in Malaysia, 5.9 per cent in Indonesia, 7.5 per cent in Thailand, 8.3 per cent in Viet Nam and 7 per cent in Cambodia (Asian Development Bank, 1993).

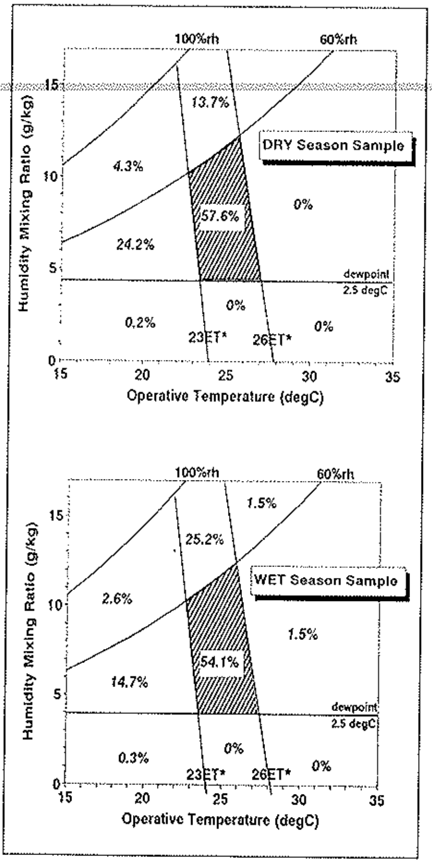
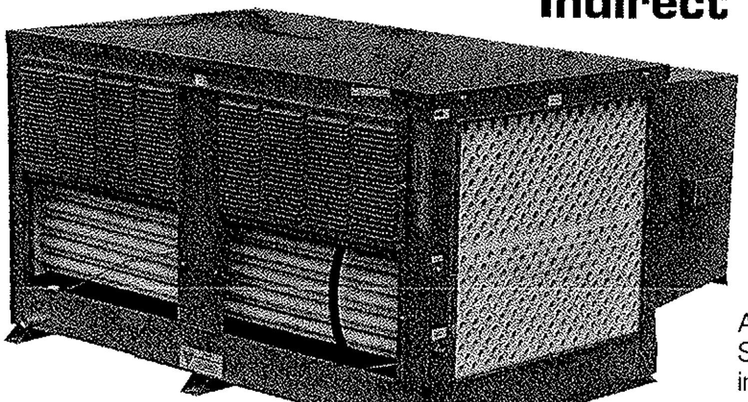


Figure 3. The distribution of indoor climatic measurements in relation to the ANSI/ASHRAE Standard 55-1992 recommended summer "comfort zone."

Associated with this economic dynamism is an escalating demand for air conditioning services. Therefore the tropics have a pressing need for their own empirical thermal comfort database, yet to date, much less research has been conducted in this part of the world compared with temperate mid-latitude climates.

Previous Comfort Research in Hot-Humid Climates. Recently there have been some field experiments on thermal comfort conducted in humid tropical locations including Singapore (de Dear et al. 1991a) and Bangkok (Busch 1990; 1992). Their results indicated that thermal requirements for environments inside tropical buildings, particularly those that are naturally ventilated, could be significantly warmer and more acceptable to their occupants than predicted by comfort models and standards based on mid-latitude research. However, the physical indoor climatic measurements in all of these studies were recorded at just one height above floor level by instrumentation, in particular the anemometry, that could not be referred to as "laboratory-grade."

Aims. The basic premise of the current field experiment was the collection of data from office buildings and their occupants



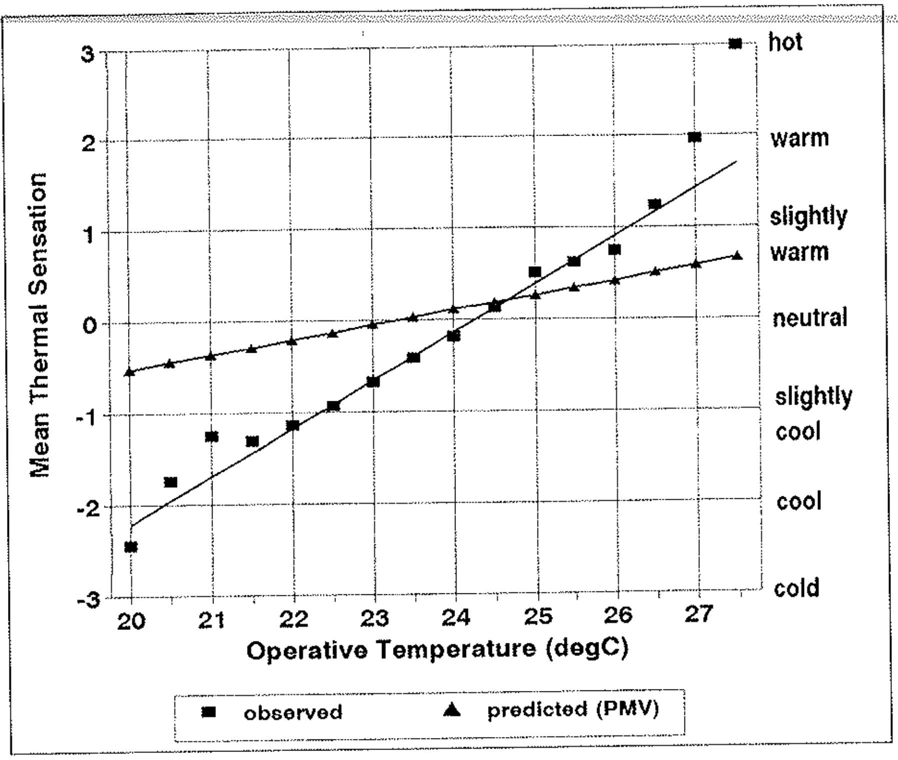


Figure 4. Mean binned thermal sensation votes observed in Townsville offices compared with predicted comfort responses using the PMV index - both seasons combined

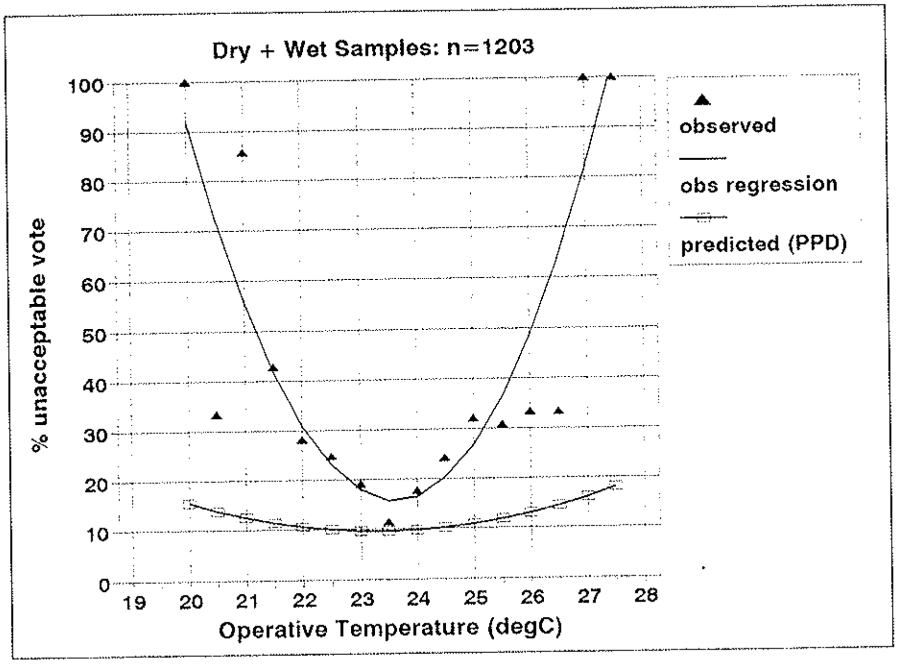


Figure 5. Observed and predicted (PPD) thermal acceptability related to operative temperature - both seasons combined

in the tropics using a package of laboratory-grade instrumentation conforming with the specifications and methods detailed in ANSI/ASHRAE Standard 55-1992, ISO 7726 and ISO 7730 standards. As such, the current project (ASHRAE RP-701) can be described as a replication of the earlier San Francisco field experiment (ASHRAE RP-462) in every detail except that it was carried out in the hot-humid climatic setting of northeast Australia.

The aims of the research are as follows:

1. To develop a database of the thermal environments and subjective responses of occupants in existing office buildings in a hot-humid climate.
2. To determine for each season (wet and dry), both the preferred thermal conditions for occupancy as well as the range of conditions found thermally acceptable by the occupants. These findings are to be compared to the conditions required by the ANSI/ASHRAE 55-1992 and ISO 7730 standards.
3. To assess the suitability of existing predictive thermal comfort indices (ET*, SET), as computed by the Pierce 2-node model used in San Francisco field experiment, and the PMV and PPD indices for use in the tropics.
4. To investigate the influence of clothing and gender, and also investigate potential acclimation effects by a) inter-seasonal comparisons, and b) comparing the hot-humid climate database with that of the earlier mid-latitude San Francisco field experiment (Schiller et al. 1988; 1990).

Methods

The Outdoor Climatic Context. The city of Townsville, at latitude 19°S on the northeast coast of Australia, lies near the climatological border between the humid and dry tropics, as depicted in Figure 1. The city's climate can best be classed as "wet and dry tropical" since rainfall and associated humidity have a marked seasonality (Nieuwolt 1977), giving rise to the "dry" and "wet" seasons in winter and summer respectively. Table 1 indicates daily maximum and minimum temperature and relative humidity recorded outdoors during the dry and wet seasons' survey periods of this study.

Mean temperatures of the dry and wet seasons (i.e. average of mean daily minima and maxima) were 19.0 and 27.0°C respectively. Of particular importance is the wet season's mean daily minimum temperature exceeding 20°C while maximum (dawn) humidities were consistently higher than 80 per cent RH at the same time.

From the human standpoint, the oppressive combination of heat and humidity persists throughout day and night during the wet season in Townsville, and therefore provides a suitable climatic setting for the stated objectives of the present project.

Buildings Surveyed. Townsville is the largest city in tropical Australia, having a population of 126,000 and performing primarily an administrative function for the far north region of Queensland. A total of 12 office buildings were selected for the study, representing a good cross-section of the city's building stock. Their key characteristics are listed in Table 2.

Subjects. Sample sizes of 628 and 606 were achieved in the dry and wet season surveys respectively. This total of 1234 sets of data was given by 836 individuals, of whom 398 were interviewed in both seasons. A summary of the background characteristics of the subjects is provided in Table 3.

Instrumentation for Indoor Climate Measurements. A mobile measurement system, "Cart Mk II," was used on-site in

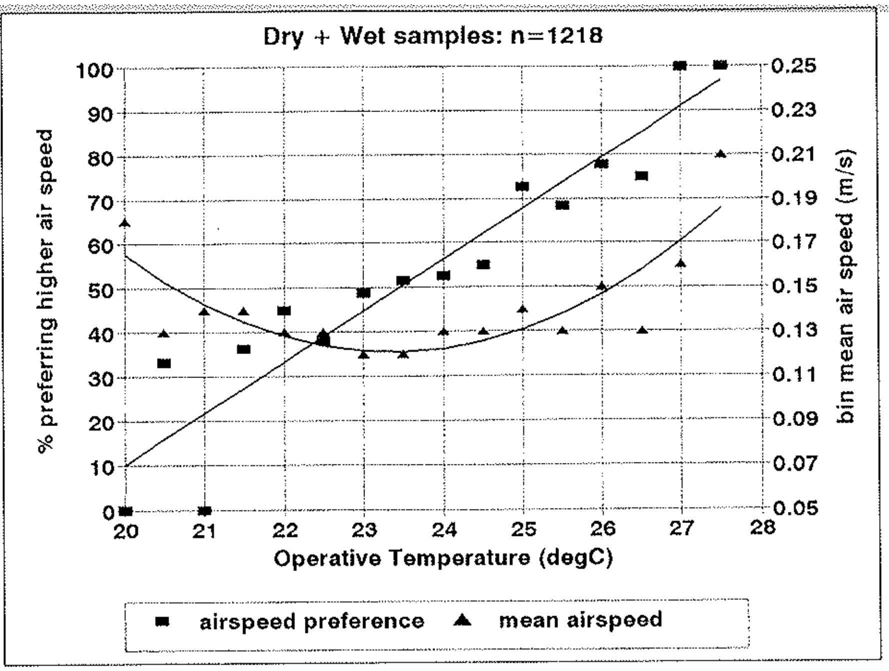


Figure 6. Air movement preferences (both seasons combined). Percentages of subjects within half degree operative temperature bins who wanted more air movement are plotted along with mean air speeds recorded within the same temperature bins.

		Dry Season	Wet Season
Temperature (degC)	max	24.4	29.8
	min	13.6	24.2
Relative Humidity (%)	max	89	87
	min	41	61

TABLE 1. Average daily maxima and minima for outdoor temperature and humidity during the two survey periods

Townsville to collect measurements of indoor physical environments. Cart Mark II is an improved version of the mobile system used in the earlier San Francisco field experiment (Benton et al. 1990) and is depicted in Figure 2.

The system's features and specifications include the following:

1. The system is capable of collecting concurrent physical data (air temperature, dew point temperature, globe temperature, radiant asymmetry, air velocity, and illuminance) from three arrays of transducers placed at 0.1m, 0.6 m and 1.1 m above floor level, representing the immediate environment of the seated subject's ankles, body and neck respectively. The "seat" of the instrument deliberately shielded the sensors in the same way that the occupant's chair shields the subject.

2. The transducers and their automatic logging meet the ANSI/ASHRAE 55-92 (1992) and ISO 7726 (1985) specifications for accuracy and response time. Air and globe temperature transducers were thermistors with accuracy within 0.2°C.

The globes were fabricated from 38mm diameter table-tennis balls painted grey to approximate the emissivity of a clothed person (ASHRAE 1993, Ch.8).

Air velocity was measured by three omni-directional, fully temperature-compensated sensors having time constants better than 0.1 s, thus permitting an assessment of turbulence in the airflow (ASHRAE 1992; Melikov 1992).

Dewpoint temperature was registered by a chilled mirror apparatus with a standard 100 ohm platinum resistance temperature device. A radiant asymmetry probe was mounted in the vertical plane at 1.1m above floor height and consisted of two hemispheric radiometers mounted back-to-back. Illuminance in the horizontal plane was measured at 1.1m above floor level by a cosine-corrected silicon photometer.

3. The data acquisition system provided a real-time display of measured values for error checking by research personnel. These data were displayed on a notebook computer mounted on the cart but out of the subject's view to avoid bias in their questionnaire responses.

Questionnaires. The initial contact with each subject involved completion of two separate questionnaires which will be referred to as the ONLINE and BACKGROUND forms. The ONLINE form was a single sheet asking for rating-scale assessments of, among other things, air movement, thermal acceptability and thermal sensations exactly at that point in time and space.

Building Code	Construction Date	Number of Floors	Area (Sq.m)	Type of Tenant	Number of Questionnaires	Air Conditioning Type	Floor Plan Layout
A	1985	3	2010	gov	100	VAV	mixed
B	1972	4	3944	gov	22	CAV	mixed
C	1986	12	17820	private	109	VAV	mixed
D	1974	4	4865	gov	45	CAV	mixed
E	1975	5	1860	gov	89	CAV	mixed
F	1975	8	4632	private	73	CAV	all open plan
G	1976	3	4851	gov	200	CAV	mixed
H	1986	5	7780	gov	203	CAV	mixed
I	1928	3	1727	gov	29	CAV	small offices
J	1975	3	2076	gov	124	VAV	mixed
K	1969	6	3942	private	33	VAV	mixed
L	1992	13	22910	gov	207	VAV	mixed

TABLE 2. Summary of the twelve office buildings surveyed

1. Air movement preferences were assessed with a direct question: "At the present moment would you like more, less, or no change in the level of air movement in your office?"

2. Thermal acceptability was assessed with the following question: "At this moment is the thermal environment acceptable to you?"

3. Thermal sensation was assessed with the usual ASHRAE seven-point scale: -3=cold, -2=cool, -1=slightly cool, 0=neutral, +1=slightly warm, +2=warm and +3=hot.

Side two of the ONLINE form consisted of clothing and activity checklists which were subsequently converted into ensemble clothing insulation and metabolic rate estimates using the data and methods specified in ANSI/ASHRAE Standard 55-92. The ONLINE questionnaire was typically completed in under five minutes.

The second form, the BACKGROUND questionnaire, required between 20 and 30 minutes to complete. It assessed various demographic characteristics of the subjects along with general information dealing with the length of time they had lived in the tropics, their exposure to air conditioning outside working hours and their general level of satisfaction with other aspects of the work environment (e.g. lighting, noise, furniture, privacy and decor).

The subjects' degree of control over their personal thermal environment was also rated, as was their environmental sensitivity, general job satisfaction and finally, general health status at the time of the interview.

The stated aims of the present paper confine the analysis mainly to the ONLINE questionnaire, drawing on the BACKGROUND database mainly for demographic and anthropometric characteristics of the samples.

Procedure: The procedure for each workstation visit was as follows:

1. Researcher approached subject at their workstation and sought their cooperation in administering the ONLINE questionnaire.

2. Researcher time-stamped the ONLINE questionnaire for subsequent matching against Cart Mk II data, then the subject completed ONLINE form.

3. The subject then left their desk and Cart Mk II was immediately wheeled into exactly the same place formerly occupied by the subject's chair.

4. A five-minute sample of the workstation's thermal environment was recorded and time-stamped by Cart Mk II.

5. During the survey, the researcher recorded additional observations (e.g. estimate of incremental clothing insulation afforded by the subject's chair, photographs, checks Cart Mk II data).

6. After both subjective and physical environmental measurements were completed, the researcher presented the BACKGROUND questionnaire to the subject and scheduled a pick-up later in the day (usually within half an hour).

Calculation of Comfort Indices. After matching data from the ONLINE questionnaires with their corresponding Cart Mk II data scan, environmental and comfort index calculations were performed with exactly the same programs as those used in the earlier San Francisco project, thus ensuring compatibility between the two databases.

Indices included operative temperature (t_o), mean radiant temperature (t_r), the New Effective Temperature (ET*), Standard Effective Temperature (SET), Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), along with the PD index (Predicted percent dissatisfied due to Draft) proposed by Fanger et al. (1988) and subsequently incorporated into ANSI/ASHRAE Standard 55-1992 (ASHRAE 1992).

For those indices having clothing insulation as an input parameter, calculations were performed twice; with and without the additional insulation effect of the subject's chair included. Recently, some discussions in thermal comfort research literature have focused on the effect of the chair on the value of clothing insulation for a seated person (e.g. de Dear 1994; Brager et al. 1994). The estimates used in this study were based on comparisons between clothing insulation measurements made by a thermal manikin seated in typical office chairs and those recorded for the manikin wearing the same ensemble but sitting in a string chair (Dr S Tanabe, pers. comm., 1993).

The program used to calculate ET* and SET indices was the 2-node FORTRAN code published by Gagge et al. (1986). For the PMV and PPD calculations, the ISO 7730 (ISO 1984) FORTRAN code was used.

Results

Indoor Climates. Table 4 provides statistical summaries of the indoor climatic measurements for the dry and wet season samples. These data represent the main thermal variables recorded at subjects' workstations by CART Mk II.

Mean air (t_a) and radiant (t_r) temperatures (averaged across the three heights measured by Cart Mk II) generally fell within the 23 to 24°C interval for both seasons. Thermal stratification was negligible with vertical air temperature gradients on average about 0.11°C/m in the occupied zone.

Average relative humidities (r_h) fell within the 50 to 60 per cent range for both seasons and air velocities (v) (averaged across three heights) were low, with a mean of 0.12 m/s and turbulence intensities (Tu) around 40 per cent.

Figure 3 presents for each season a comparison of the indoor thermal environments found in Townsville with the ANSI/ASHRAE 55-1992 comfort standard in psychrometric chart format. Since the standard's comfort zone has four edges, these can be projected to the margins of the psychrometric chart to delineate eight distinct regions around the cen-

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tral "comfort zone" which is the Standard's 90 per cent thermal acceptability prescription for summer conditions (the shaded region in Figure 3 between 23 and 26°C ET*).

The percentages depicted in Figure 3 represent the number of each season's sample falling in each of the comfort chart's nine regions. Barely half of the indoor conditions sampled in Townsville buildings fell within ANSI/ASHRAE 55-1992's summer comfort zone. Noteworthy in terms of energy conservation concerns (or lack of them) is the finding that about a quarter of the Townsville offices surveyed had cooler-than-recommended temperatures.

Clothing and Metabolic Factors. Table 5 presents summaries of the main personal thermal variables of clothing insulation and metabolic rates for each season. Intrinsic clothing ensemble insulation based on the garment clo-values published in ANSI/ASHRAE Standard 55-1992 and was generally near the standard's assumed summer value of 0.5 clo, irrespective of gender.

There was, however, some interseasonal variability, with the wet season's ensemble average being about 0.1 clo less than that of the dry season ($t=10.8$, $df=1232$, $p<0.01$).

Concomitant with this seasonal decrease was a decrease in the interindividual variability (standard deviation) from about 0.2 clo in the dry season towards 0.1 clo in the wet season, suggesting that the degrees of freedom for individuals to thermoregulate their clothing decreased as the local office dress-code minimum was approached during the wet season.

Also listed in Table 5 is a second set of thermal insulation estimates which take into account the effect of the chairs on which subjects were sitting at the time they completed the ONLINE questionnaire. On average, the chair insulation increment amounted to 0.15 clo, lifting the insulation values used in subsequent thermal comfort index calculations to 0.7 and 0.6 clo in the dry and wet season surveys respectively.

Based on a behaviour/activity checklist referring to the hour just prior to sitting down to fill in the ONLINE questionnaire, metabolic rates of the subjects were estimated to be, on average, 78 W/m^2 or 1.3 met in both seasons and for both sexes.

Calculated Comfort Indices. Table 6 presents a statistical summary of the thermal environmental and comfort indices broken down by season. These indices include operative temperature to (average of t_a and t_r), ET*, SET, PMV/PPD indices and the draft dissatisfaction index, PD. On average, t_0, ET* and SET values fell within the 23 - 24°C range while the PMV calculations indicate marginally cooler than neutral conditions (-0.2 to - 0.3).

Contained at the bottom of these tables is a second set of index calculations taking into account the effects of chair insulation as discussed above. The average chair effect was reflected by an increase in mean SET by 1.4°C, an increase of 0.3 PMV units and a reduction of PPD by about 3 per cent.

Subjective Thermal Sensations in Townsville Offices. Mean thermal sensation on the seven-point scale was marginally cooler than "neutral" (-0.3 to -0.4) for both seasons. In view of the similarity of thermal sensation responses between seasons, subsequent analyses were conducted on the combined wet and dry season data set. The strength of association and sensitivity of thermal sensation votes to temperature variations are most easily quantified using linear correlation/regression techniques.

The analysis proceeded by taking mean votes within successive half-degree operative temperature bins as the dependent variable rather than individual sensation votes. By weighting each data pair with the number of subjects falling in its respective bin, the effect of relatively large residuals at the less frequently encountered temperature extremes was deemphasised.

As depicted in Figure 4, the regression line fitted to these bin means ("observed" in the legend) was highly significant ($F=636.2$; $Prob<0.0001$; $r^2=0.97$) with a standard error on the regression coefficient was 0.02 ($Prob<0.0001$). Solving the fitted equation (below) for a thermal sensation vote of zero (neutral) gives a temperature of 24.3°C. The regression coefficient (gradient) indicates that Townsville office workers changed their thermal sensations by one unit every two degrees change in temperature:

mean ASHRAE sensation = $0.522 * t_o - 12.67$

Superimposed on the same graph in Figure 4 is the regression equation for mean binned PMV index values ("predicted" in the legend) which included the effects of chair insulation. Clearly the PMV model's predictions underestimate the observed sensitivity to operative temperature.

	Season	Dry	Wet
	Sample Size	628	606
Gender	male	42%	41%
	female	58%	59%
Age (year)	mean	33.9	32.8
	standard deviation	10.5	10.0
	minimum	17.0	17.0
	maximum	64.0	62.0
Height (cm)	mean	170.2	169.9
	standard deviation	9.8	9.9
	minimum	148.7	130.0
	maximum	198.0	198.0
Weight (kg)	mean	69.5	69.2
	standard deviation	14.8	14.7
	minimum	37.0	40.0
	maximum	126.0	145.0
Years in in tropics	mean	20.5	20.8
	standard deviation	14.5	14.0
	minimum	0.0	0.0
	maximum	64.5	59.9
Highest education	high school	54%	53%
	diploma/degree	40%	41%
	postgrad university	6%	6%
Ethnic Background	Aborigine	4%	3%
	Asian	1%	2%
	Caucasian	93%	94%
	Other	1%	1%

TABLE 3. *Summary of the office workers surveyed*

Assessment of the Thermal Acceptability of Townsville Offices. As with the thermal sensation responses, the acceptability data were binned by t_o and the resulting percentages of dissatisfaction have been plotted as a function of temperature in Figure 5 (denoted as "observed" in the legend).

The second-order polynomial weighted regression curve indicates minimum levels of thermal dissatisfaction at $t_o=23.5$°C and it was only at this central temperature that the ANSI/ASHRAE 55-1992 standard's 90 per cent acceptability goal was actually met in the Townsville sample. Using the fitted "observed" curve in Figure 5 as a guide, 80 per cent acceptability appears to have been achieved between 22.5 - 24.5°C, a somewhat narrower range than the three degree band suggested in ANSI/ASHRAE 55-1992 and ISO 7730 for 90 per cent acceptability.

An implication of the Townsville thermal acceptability data as depicted in Figure 5 is that there were large numbers of subjects who considered their workstation environments to be thermally unacceptable despite the fact that, on the objective criteria of t_0 and humidity at least, they fulfilled the criteria specified in ANSI/ASHRAE Standard 55-1992 and ISO 7730.

A total of 255 subjects voted that their thermal environments were "unacceptable." Of this subset of thermally dissatisfied subjects, more than half (132 subjects or 52 per cent) were in environments that fulfilled the ANSI/ASHRAE Standard 55-1992 comfort zone criteria. Conversely, 405 of the 955 subjects (i.e. 42 per cent) who found their thermal environments "acceptable" were actually in conditions outside the ANSI/ASHRAE Standard 55-1992 comfort zone.

Air Movement Preferences. The actual levels of air movement measured with CART Mk II at the sampled workstations (Table 4) of 0.12 m/s with about 40 per cent turbulence intensity were quite consistent throughout the 12 buildings and across both seasons, as indicated by the small standard deviations.

A majority of subjects in both seasons still indicated a preference for air movement levels different to those prevailing at the time of their interview. As seen in Figure 6, from about 23.5°C on up to the warmest temperatures tested in this study, a majority of subjects wanted higher levels of air movement than they were actually receiving at the time of their interviews, despite the fact that the latter were exactly within the ranges prescribed in ANSI/ASHRAE Standard 55 (between 0.15 and 0.2 m/s).

Discussion

Comparisons Between Indices, Models and Observed Data. As seen in Figure 4, the "Predicted" (PMV) regression model, with chair insulation included, intersected the "neutral" (zero) sensation about half a degree cooler than the actual thermal sensation votes' regression model did. This finding can be regarded as indicating quite good agreement between prediction and observation. However, the PMV index performed much less satisfactorily under non-neutral conditions, giving discrepancies of the order of half a sensation unit at the margins of the comfort zone (23 and 26°C).

	Season	Dry	Wet
	Sample Size	627	604
Air Temperature (degC)	(average of 3 heights)		
	mean	23.3	23.6
	standard deviation	0.9	1.0
	minimum	20.1	21.3
	maximum	25.7	27.6
Mean Radiant Temperature (degC)	(average of 3 heights)		
	mean	23.5	23.9
	standard deviation	0.9	1.0
	minimum	19.2	21.0
	maximum	25.8	27.8
Plane Radiant Asymmetry (degC)	(1.1 m above floor)		
	mean	-0.2	-0.4
	standard deviation	0.8	1.0
	minimum	-7.4	-6.5
	maximum	1.6	5.0
Dew Point Temperature (degC)			
	mean	12.3	14.3
	standard deviation	2.6	2.0
	minimum	6.8	10.4
	maximum	17.6	19.1
Relative Humidity (%)	mean	50.8	56.3
	standard deviation	6.7	6.3
	minimum	34.0	44.0
	maximum	69.0	71.0
Vapor Pressure (hPa)	mean	14.5	16.4
	standard deviation	2.5	2.1
	minimum	9.8	12.6
	maximum	20.1	22.1
Air Velocity (m/s)	(average of 3 heights)		
	mean	0.12	0.13
	standard deviation	0.03	0.04
	minimum	0.10	0.10
	maximum	0.25	0.66
Turbulence Intensity (%)	(average of 3 heights)		
	mean	38.7	42.6
	standard deviation	24.4	32.4
	minimum	5.0	5.0
	maximum	195.0	325.0

TABLE 4. Statistical summary of the indoor climatic measurements

Season	Dry			Wet		
Gender	Male	Female	Combined	Male	Female	Combined
Sample Size	266	362	628	248	357	606
Intrinsic Clothing Insulation (clo)						
mean	0.52	0.55	0.54	0.45	0.44	0.44
standard deviation	0.17	0.20	0.19	0.12	0.13	0.13
minimum	0.25	0.25	0.25	0.21	0.20	0.20
maximum	1.09	1.38	1.38	1.15	1.02	1.15
Clothing + Chair Insulation (clo)						
mean	0.68	0.70	0.69	0.61	0.59	0.59
standard deviation	0.18	0.20	0.19	0.13	0.14	0.13
minimum	0.32	0.40	0.32	0.30	0.29	0.29
maximum	1.24	1.53	1.53	1.30	1.17	1.30
Metabolism (W/m*m)						
mean	78.2	77.5	77.8	77.8	77.5	77.6
standard deviation	12.3	13.0	12.7	13.4	13.7	13.6
minimum	58.2	58.2	58.2	58.2	58.2	58.2
maximum	116.4	116.4	116.4	116.4	151.3	151.3

TABLE 5. Statistical summary of the personal thermal parameters - clothing insulation and metabolic rate

The very shallow gradient of PMV on temperature, depicted in Figure 4, suggests that subjects were effectively adjusting other parameters in their heat balance, such as clothing, in a way that largely compensated for ambient temperature departures from neutrality, in the heat-balance sense at least. On the questionnaire however, the effects of these clothing adjustments appeared to have been overlooked as subjects were casting their thermal sensation votes, resulting in a much higher thermal sensitivity than theory (PMV) predicted.

Turning to observed and predicted levels of thermal acceptability/dissatisfaction, Figure 5 shows that both agreed on a single optimum temperature of 23.5°C. However, the absolute levels of dissatisfaction predicted by PPD considerably underestimated the observations across the full range of temperatures encountered in this study, except for 23.5°C.

In effect, the subjects were much less accepting of temperatures away from 23.5°C than the PPD index predicted. For example, at the warm margin of the comfort zone (26°C), thermal dissatisfaction was observed to be as much as 20 per cent above the level predicted by the index.

Comparisons Between Observed Comfort Data and the Standards. Perhaps the most vexatious building occupant for the facilities manager or HVAC maintenance engineer is the one who complains about their air conditioning despite the fact that his/her workstation's physical environment matches the specifications laid down in the standards. Ever since Fanger's (1970) PPD index gave quantitative expression to the truism long recognized by HVAC maintenance engineers — that "you can't please all of the people all of the time," such persons have been expected to represent at least 5 per cent to 10 per cent of building occupants.

In Townsville, 690 of the 1234 workstations visited had indoor climates within the ANSI/ASHRAE Standard 55-1992's comfort zone, but only 80 per cent of the occupants of those workstations found them thermally acceptable; not the 90 per cent suggested in the Standard.

To further confirm that this level of dissatisfaction was indeed anomalously high, the Predicted Percentage Dissatisfied index was calculated for all 690 sets of observations meeting Standard 55's criteria, and the average came to just 12 per cent PPD, or about half of the dissatisfaction level actually observed.

In searching for explanations for the dissatisfaction within the comfort zone observed in Townsville, the first strategy was an investigation of factors known to influence comfort but not included in the preceding analyses. Vertical temperature stratification is suggested in ANSI/ASHRAE 55 as a potential source of complaint. The standard specifies that the maximum allowable vertical gradient within the occupied zone is 1.9°C/m, yet none of the cases of unexplained thermal dissatisfaction exceeded this guideline. Standard 55 suggests that radiant temperature asymmetries in the vertical plane may be a source of complaint, but again none of the cases under investigation exceeded the Standard's plane radiant asymmetry limit of 10°C (see Table 4).

Standard 55 also suggests that air movement characteristics can be a potential source of complaint in an otherwise acceptable thermal environment. Unwanted local cooling due to excessive velocity or turbulence is defined as draft. The standard recommends the application of the Fanger et al. (1988) PD model of draft risk to minimise complaints of this type, and specifies that index values should not exceed 15 per cent. In only nine of the unexplained thermal dissatisfaction cases in Townsville was there a PD index value greater than the suggested limit.

In contrast, 95 of the thermally dissatisfied subjects within the comfort zone actually expressed a desire for higher, not lower air speeds, on the ONLINE questionnaire's air movement preference scale. Clearly draft is not as important a comfort issue in the hot-humid climate zone as it is in cooler regions where the draft limits were originally derived. Therefore the most common causes of dissatisfaction within the "comfort zone" in this tropical study were air speeds and/or turbulence intensities being too low, despite their compliance with the prescriptions of ANSI/ASHRAE Standard 55.

	Season	Dry	Wet
	Sample Size	627	604
Operative Temp. (degC)	mean	23.4	23.8
	standard deviation	0.9	1.0
	minimum	19.8	21.2
	maximum	25.7	27.7
ET* (degC)	mean	23.4	23.9
	standard deviation	0.9	1.0
	minimum	19.8	21.2
	maximum	25.6	28.2
SET (degC)	mean	23.3	22.9
	standard deviation	1.8	1.5
	minimum	18.8	19.4
	maximum	30.7	28.7
PMV	mean	-0.2	-0.3
	standard deviation	0.6	0.6
	minimum	-2.4	-2.1
	maximum	1.1	1.4
PPD (%)	mean	12.4	14.0
	standard deviation	11.8	13.6
	minimum	5.0	5.0
	maximum	91.8	82.5
Predicted Dissatisfaction from Drafts - PD (%)	mean	9.7	11.4
	standard deviation	3.3	5.7
	minimum	5.3	5.0
	maximum	32.4	76.8
SET (degC) (incl. chair insulation)	mean	24.7	24.3
	standard deviation	1.7	1.5
	minimum	20.1	20.8
	maximum	31.8	30.2
PMV (incl. chair insulation)	mean	0.1	0.0
	standard deviation	0.5	0.5
	minimum	-1.9	-1.6
	maximum	1.2	1.5
PPD (%) (incl. chair insulation)	mean	9.9	10.4
	standard deviation	7.1	7.9
	minimum	5.0	5.0
	maximum	69.5	55.8

TABLE 6. Statistical summary of the calculated indoor climatic and thermal comfort indices

Effects of Season on Comfort Responses. The meteorological data in Table 1 indicated a clear contrast between the hot-humid conditions of the wet season and the warm-arid conditions of the dry season. This raises the question of whether or not such a seasonal climatic forcing has any effect on the thermal comfort responses of office workers in air conditioned buildings.

In terms of clothing patterns in Townsville, there seemed to be some seasonal adjustment, with average intrinsic insulation levels being reduced by about 0.1 clo from the dry to the wet seasons (Table 5). However, in terms of neutralities on the sensation scale thermal acceptability, the interseasonal differences were, at most, within half a degree of each other and of no statistical, or indeed, engineering significance.

Effects of Gender on Comfort Responses. Earlier field studies of thermal comfort in office buildings have noted differences in thermal requirements of the sexes (e.g. Fishman and Pimbert 1979). Very often, however, such differences have been traced back to differences in clothing levels, with females having larger interseasonal and interindividual variances than males in the same environments.

In Townsville, there were no differences between the sexes in this regard, as reflected in the coincidence of the sexes' neutralities which were derived from weighted linear regressions of their thermal sensation votes on to (males = 24.2°C; females = 24.3°C).

However, despite this similarity between the sexes' thermal neutralities, the same could not be said of thermal acceptability. In the total sample of 1234 subjects comprising 58 per cent females and 42 per cent males, the former were overrepresented in the group expressing thermal dissatisfaction (68 per cent female; 32 per cent male; χ^2=12.9, df=1, Prob<0.005). No physical (i.e. environmental, clothing or metabolic) explanation can be offered for this difference between the sexes in Townsville.

Comparison with the Earlier ASHRAE-Sponsored Field Experiment in San Francisco. In a thorough re-analysis of the San Francisco database, Brager et al (1994) recently applied the latest clothing garment insulation estimates published in ANSI/ASHRAE 55-1992, factored in the insulation effect of chairs, and also applied a more realistic estimate of subjects' metabolic rates to the results. The net effect of this fine tuning was to bring PMV predicted neutrality to within 0.2°C of the 22.4°C actually observed in San Francisco.

The Townsville thermal insulation and

metabolic estimation methods are perfectly consistent with the Brager revisions, and the result was also a reasonably good prediction of neutrality by the PMV index (within a degree). Therefore a majority of the 2°C difference between San Francisco and Townsville neutralities has been explained by the physical input parameters of the PMV index, in particular, clothing.

In comparison to San Francisco subjects, the hot-humid subjects were considerably more sensitive to temperature variations. In San Francisco, Schiller et al. (1988) found a gradient of about one sensation unit per 3°C, which coincides with the gradients typically found in mid-latitude climate chamber experiments. However, in Townsville the figure was closer to 2°C and although Fanger's comfort model (1970) indicates that $\partial PMV/\partial T$ is an inverse function of clothing insulation, the magnitude of the observed thermal sensitivity increase was over three times that predicted on the basis of clothing differences between the San Francisco and Townsville subjects.

Conclusions

- A replication of the ASHRAE-sponsored San Francisco field experiment (RP-462) was performed in 12 air conditioned office buildings located in the tropical city of Townsville, Australia. A total of 836 subjects provided 1234 sets of data spread across both the wet and dry seasons. The experiment used the San Francisco questionnaires with some minor adaptations to local language and climatic conditions. Indoor climatic data were collected by a mobile cart carrying laboratory-grade instrumentation complying with ANSI/ASHRAE Standard 55 and ISO 7726 recommendations for accuracy and response times.
- Clothing insulation levels approximated the ANSI/ASHRAE Standard 55 assumed summer value of 0.5 clo, with slightly more (0.1 clo) being worn in the dry season compared to the wet. Chairs were estimated to add 0.15 clo to the clothing insulation of the office workers. Their metabolic rates were estimated on average to be 78 W/m^2 or 1.3 met. It is essential that clothing, chair and metabolic effects be included in any comfort calculations.
- Group mean thermal sensations showed a heightened senstivity to temperature, changing approximately one unit on the ASHRAE 7-point scale per 2°C change in operative temperature.
- Thermal acceptability peaked at about 23.5°C in Townsville's air conditioned offices. Therefore this temperature can be regarded as an empirically derived design criterion for office air conditioning in the tropics. Because of the heightened thermal sensitivity referred to in the preceding point, thermal acceptability rapidly tapered off to 80 per cent at 22.5 and 24.5°C in Townsville. Therefore the design criteria should be stated as 23.5°C ±1°C.
- The PMV index with the effects of chair insulation taken into account accurately predicted optimum temperatures of the Townsville subjects if defined in terms of thermal acceptability.
- In Townsville's air conditioned offices, draft or unwanted local cooling due to excessive air movement was much less of a problem than insufficient air movement. Most of the thermal dissatisfaction expressed by subjects whose thermal environments fell within the ANSI/ASHRAE Standard 55 summer comfort zone appeared related to the air at their workstation being too still.

These findings suggest that draft guidelines in Standard 55 and also ISO 7730 may be inappropriate for hot-humid climate zones and that 0.2 m/s should not be regarded as the upper limit of air speed permissible in tropical office buildings. Indeed, the current study in Townsville lends support to the use of ceiling and desk fans to supplement and possibly replace some of the air cooling required for comfort in tropical office buildings.

- There was little difference between the sexes in terms of thermal sensations, although there were significantly more frequent expressions of thermal dissatisfaction from the females in the sample, despite their thermal environments being no different from the males'.
- The effects of Townsville's hot-humid/warm-dry seasonality on thermal comfort responses of office workers was minor and of no practical engineering significance.
- In comparison to the earlier ASHRAE

field experiment in San Francisco (RP-462), neutralities in Townsville were approximately 2°C warmer. However, the relatively good prediction of both experiments' neutralities by the PMV model suggests that most of this offset can be explained by differences in physical parameters, notably clothing. Where the San Francisco and Townsville office populations were significantly different, however, was in the dependence of thermal sensation on temperature, with Townsville's office workers being the more sensitive.

- The discovery of significant differences in thermal sensitivity, acceptability and air movement preferences of office populations who have been naturally acclimatized to a wet/dry tropical climate highlights the importance of extending this series of ASHRAE-sponsored field validation experiments to other climatic extremes as well; notably cold climates and hot-dry climates. ANSI/ASHRAE Standard 55 requires these detailed validations before it can be classed as an international standard.

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