Adaptive Thermal Comfort:
Background, Simulations, Future Directions

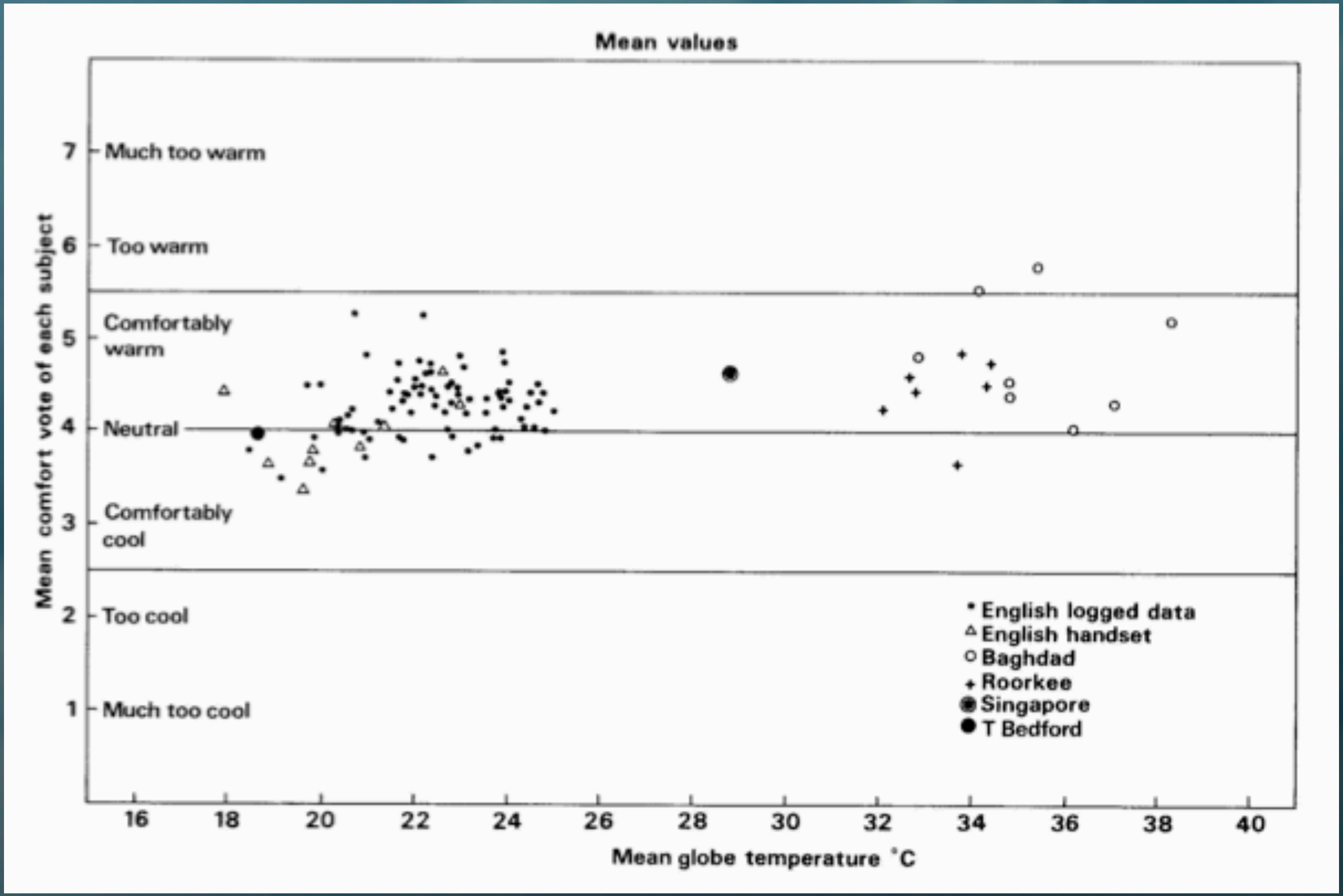
Richard de Dear, PhD

Faculty of Architecture, Design and Planning
University of Sydney, Australia

A Brief History of Adaptive Comfort

- Charles Webb (Building Research Establishment UK) is regarded by Michael Humphreys as the originator of the adaptive comfort concept
- Webb conducted longitudinal field studies in Singapore, Baghdad, north India and north London during the 1960s
- He noticed that building occupants seemed to be *most comfortable in the mean temperatures to which they were exposed*.
- He suggested that they had *adapted* to their indoor climates

Humphreys and Nicol (1970)



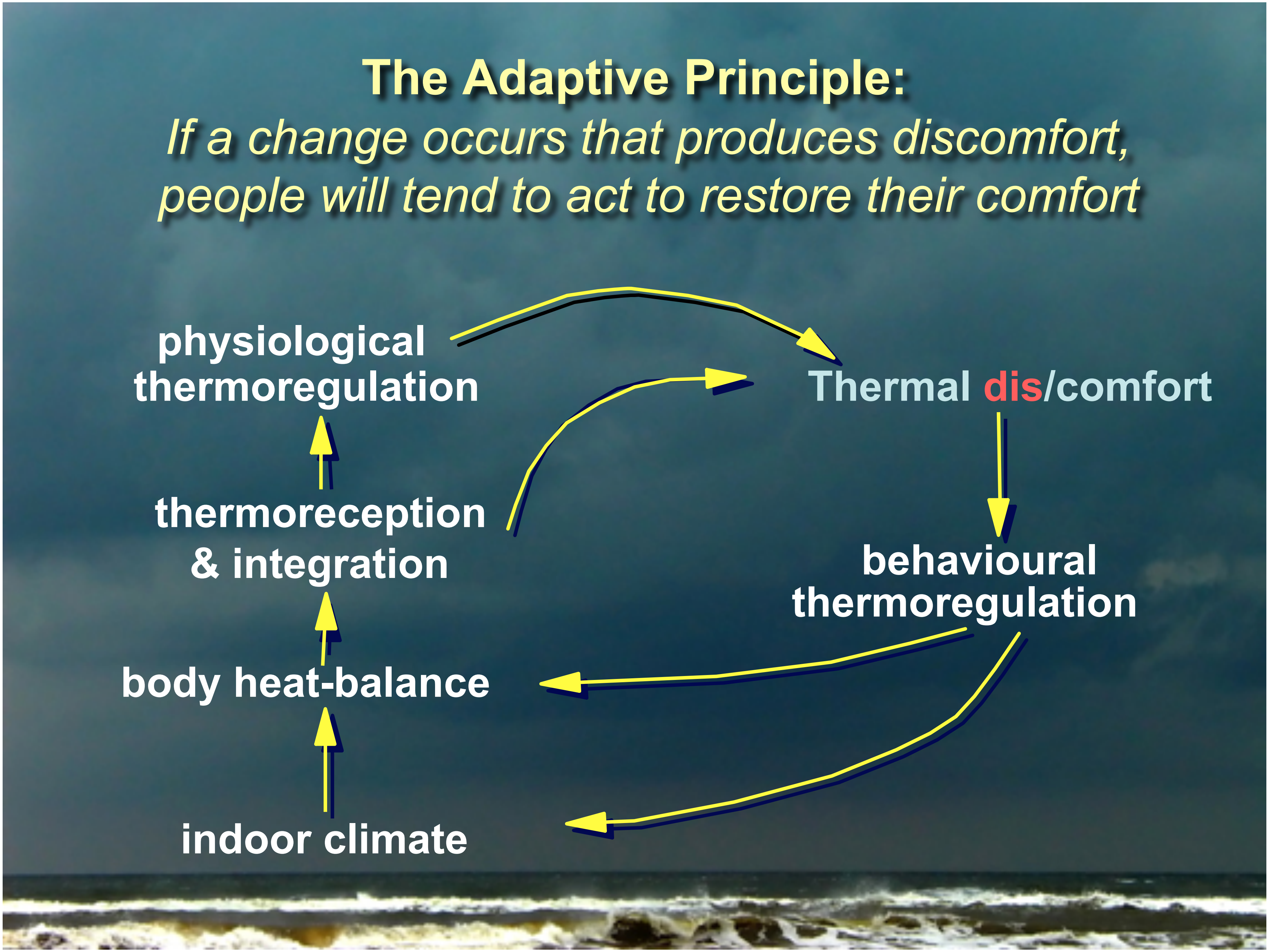
Mean monthly comfort votes and indoor temperature – Singapore, England, India, Baghdad

Nicol and Humphreys 1972

Nicol and Humphreys proposed the idea that building occupants and their indoor climate were two parts of an *integrated, self-regulating (feedback) system*.

They postulated the adaptive principle: "*If a change occurs that produces discomfort, people will tend to act to restore their comfort*"

Behavioural adaptation (personal & environmental)


The Adaptive Principle:
If a change occurs that produces discomfort, people will tend to act to restore their comfort
physiological thermoregulation
Thermal dis/comfort
thermoreception & integration
behavioural thermoregulation
body heat-balance
indoor climate

Humphreys' Meta-Analysis

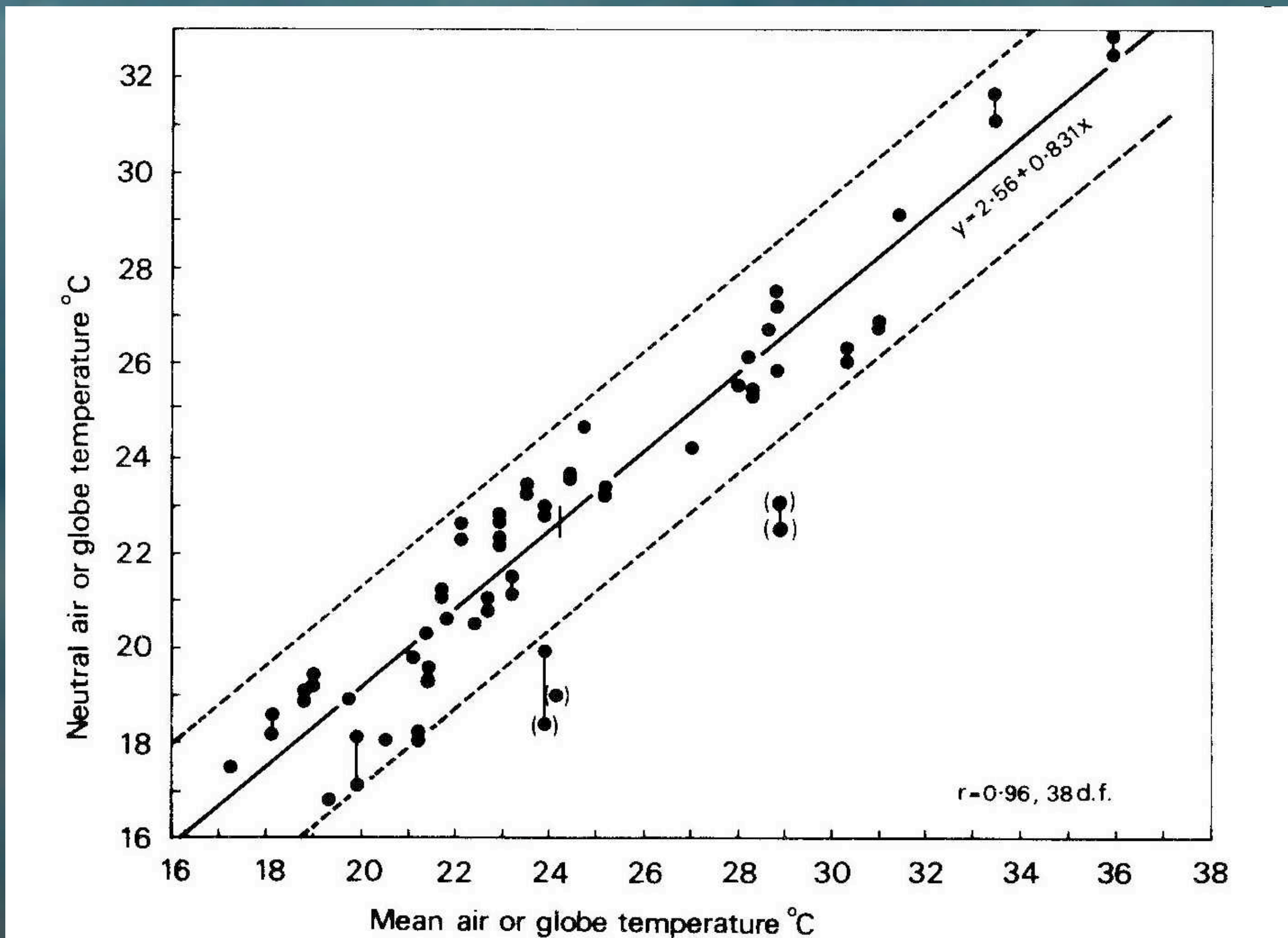
To test the adaptive feedback concept Humphreys compiled a database of all the field studies that had been published by the mid-1970s. From each he extracted:

- mean indoor temperature recorded for each study
  (stimulus variable – X)

- indoor temperature at which comfort was observed,
  usually referred to as "neutrality"
  (response variable - Y)

Field data came from all over the world (from Russia, USA, UK, Australia, western Europe, Scandinavia, India, Africa *etc*)

Humphreys' Meta-Analysis (1975)

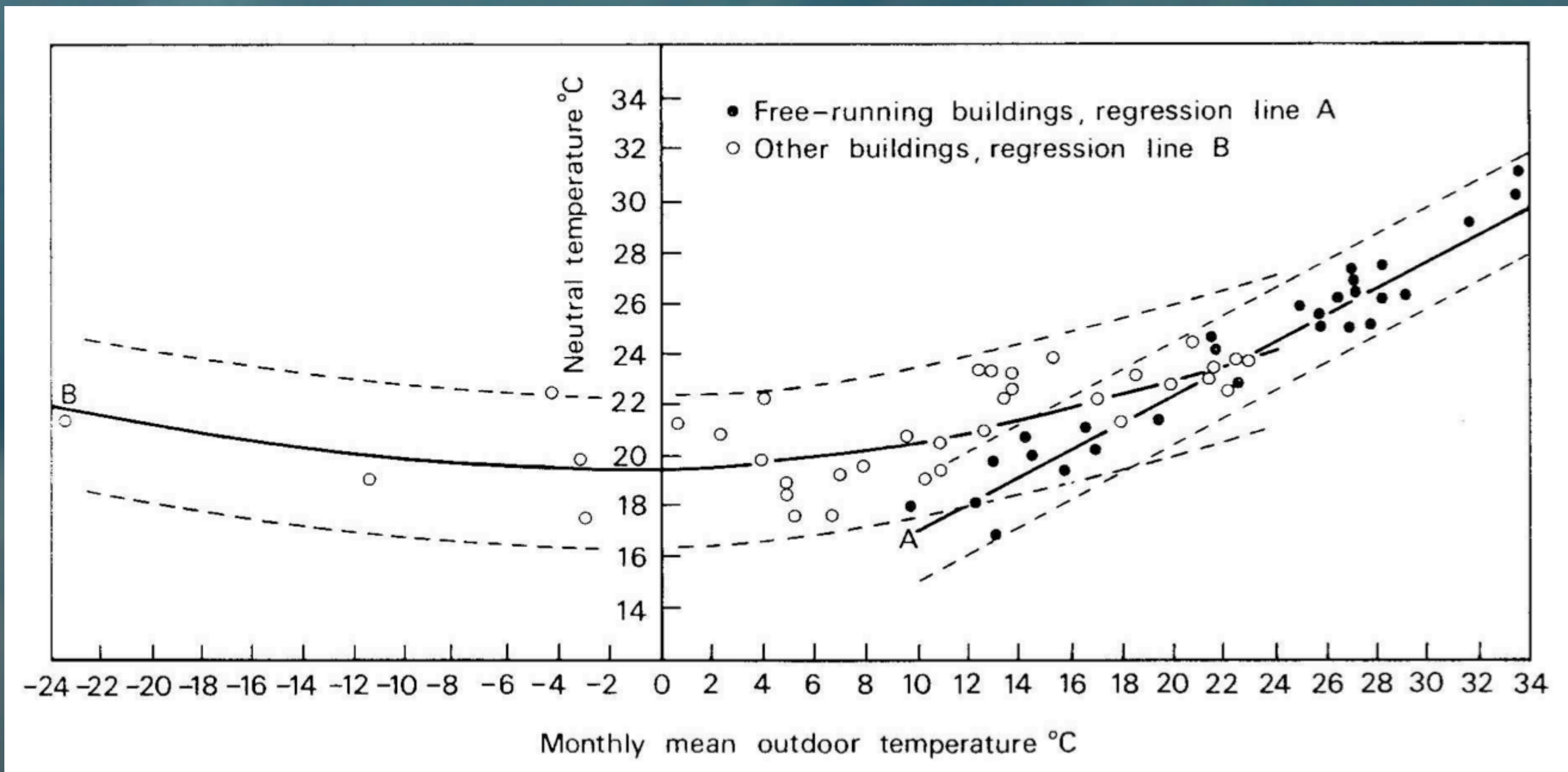


Auliciems

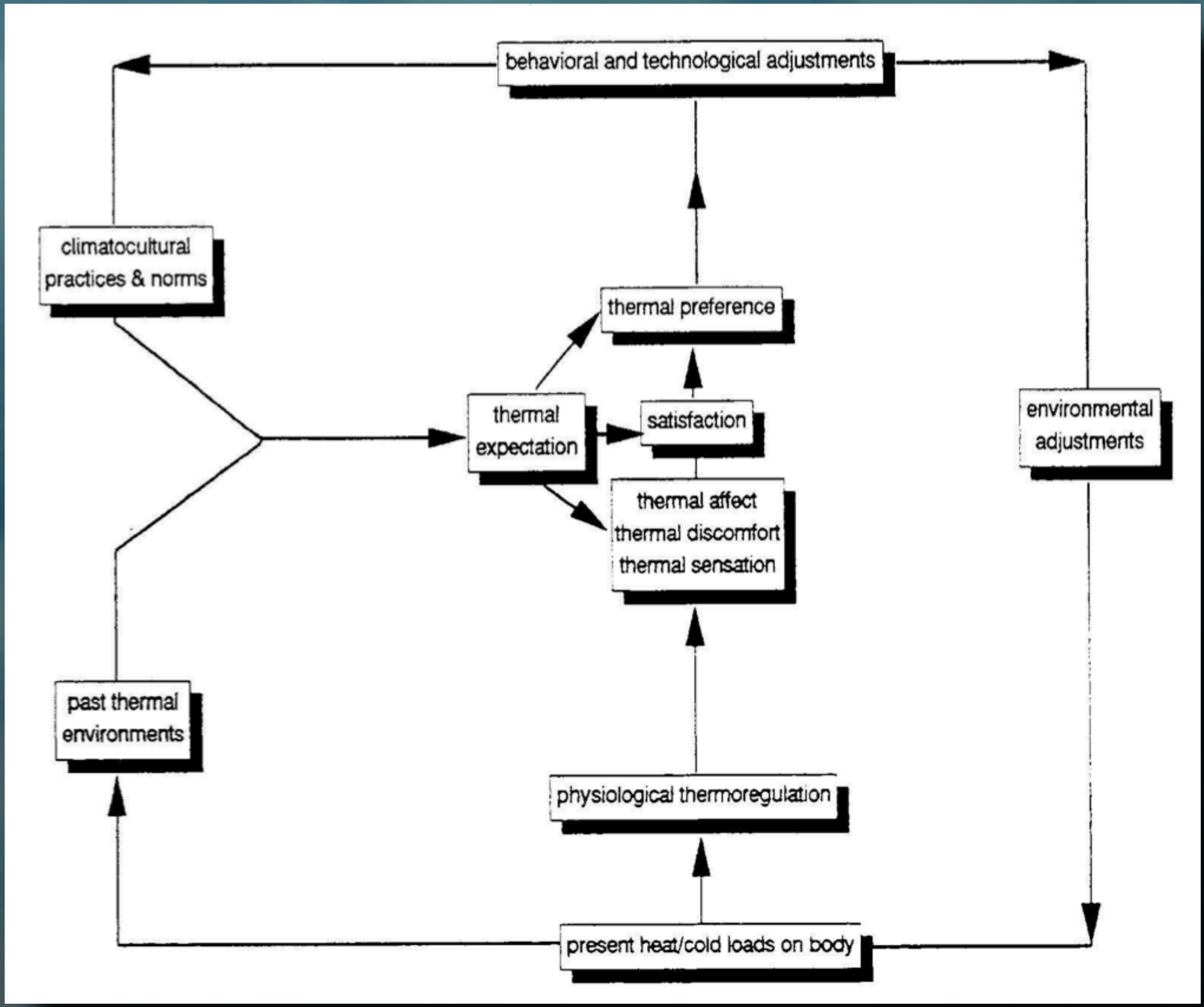
Upon hearing Humphreys' findings at a seminar in the late 1970s, Andris Auliciems, a self-confessed "climatic determinist" (!) opined that the *driver for adaptation* was not only indoor temperature, but also *outdoor climate*:

- physiological adaptation (acclimatisation)
- behavioural (adjustment)
- psychological (expectation)
- cultural (technology)

Humphreys' 2nd Meta-Analysis (1978)



Auliciems' Adaptive Model (1981)



De Dear

A PhD student under Andris Auliciems at the University of Queensland (Australia) in 1981 looked at this topic and noticed two things:

- Humphreys', Nicol's and Auliciems' adaptive comfort concept was not getting traction

- Fanger's ingenious heat-balance approach to comfort had displaced the adaptive concept and its supporting evidence

De Dear

Pitted these competing hypotheses against each other (adaptive versus heat-balance) in a series of "*field experiments*" in Australia:

- tropical Darwin, sub-tropical Brisbane, temperate Melbourne
- naturally ventilated and centrally air-conditioned office buildings
- collected all six input parameters for Fanger's PMV model
- compared *actual* and *predicted* comfort

Systematic discrepancies were found, particularly in the warmer climate zones, that couldn't be explained by the classic six comfort parameters in Fanger's heat-balance model (PMV).

The ASHRAE Comfort Database

- In the early 1990s ASHRAE got curious about the gap between comfort *theory and practice*
- ASHRAE commissioned thermal comfort field experiments…
  - *objective measurements* of indoor climate with laboratory precision
  - *subjective assessments* of those conditions using standardised questionnaires
- Data from those studies (and many others) over many years were harmonized and consolidated into a database and placed in the public domain in 1997
(look for Richard de Dear here *http://sydney.edu.au*)

The ASHRAE Adaptive Comfort Project

(de Dear and Brager 1998 *ASHRAE Transactions*)

- circa 21,000 observations (indoor climate & comfort surveys)
  - 160 buildings
  - 4 continents
  - range of climate zones

- Simultaneous and contiguous observations :
  - *objective* indoor climate
  - *subjective* comfort

Adaptive Comfort Standards

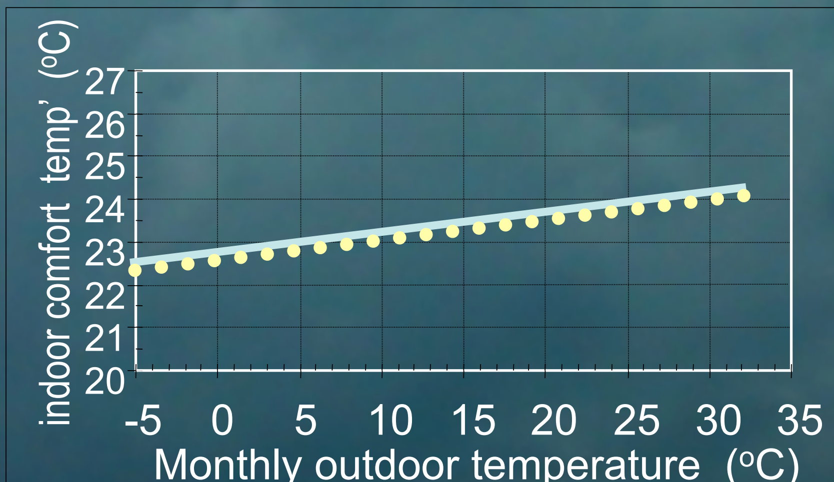
Driven largely by concerns about global climate change, but also the failure of tightly controlled and uniform indoor climates to deliver universal thermal comfort to building occupants, the focus in the last decade has been on developing adaptive comfort *standards and guidelines:*

- ASHRAE Standard 55-2004
  "*Thermal environmental conditions for human occupancy*"

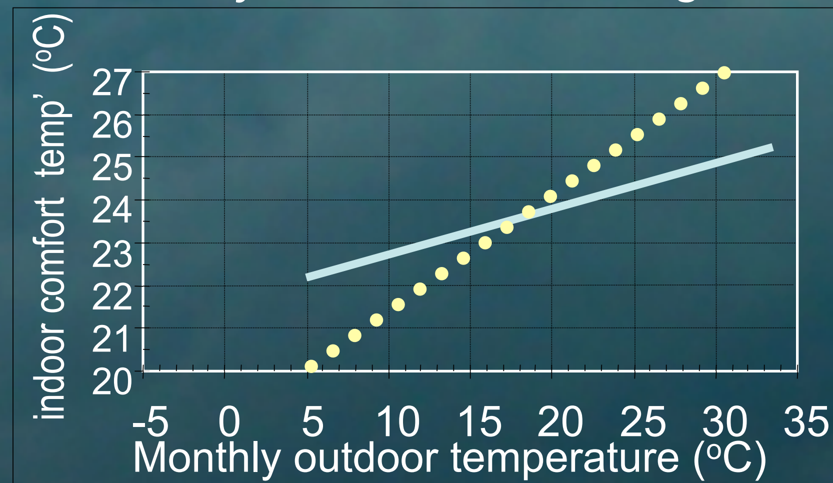
- CEN Standard EN15252-2007
  "*Indoor environmental input parameters for design and assessment of energy performance of buildings*"

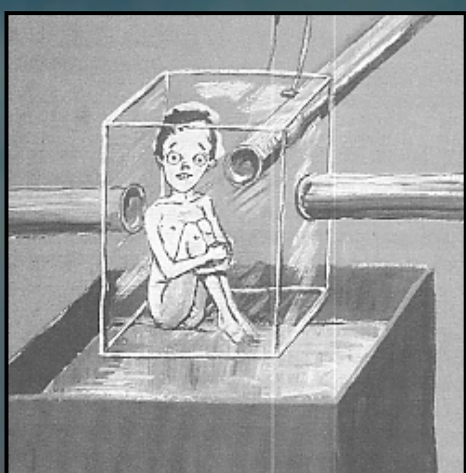
ASHRAE RP-884 database analysis

Centrally-controlled HVAC buildings

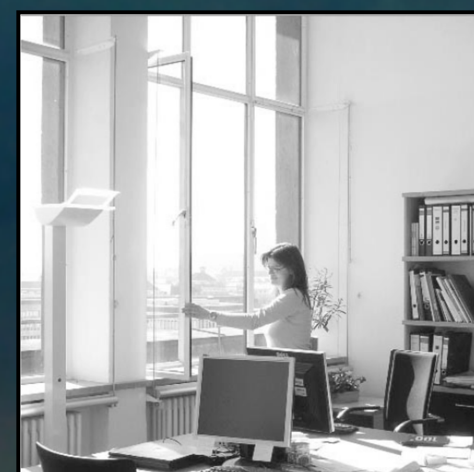


Naturally ventilated buildings



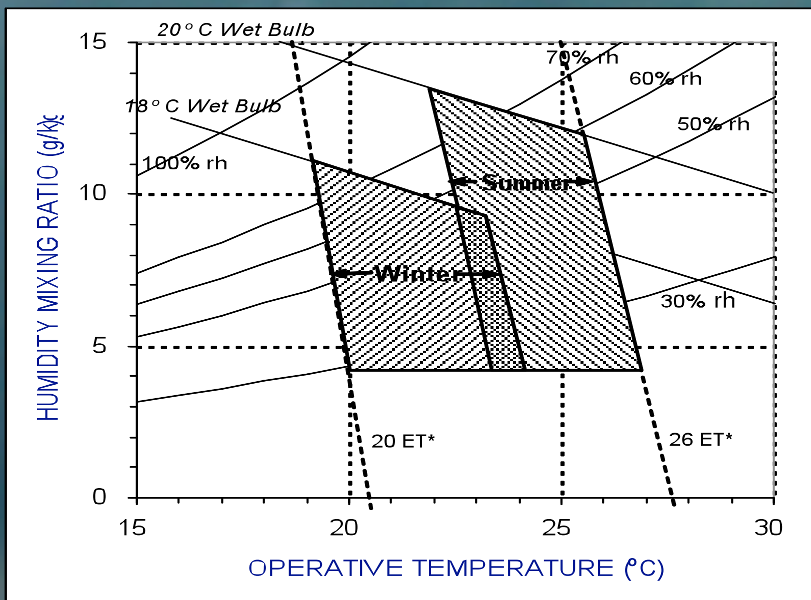


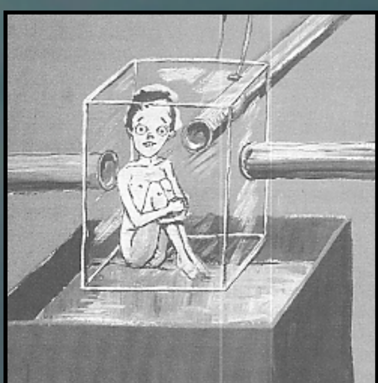
Predicted: static comfort model (PMV)
Observed: Field-based adaptive model



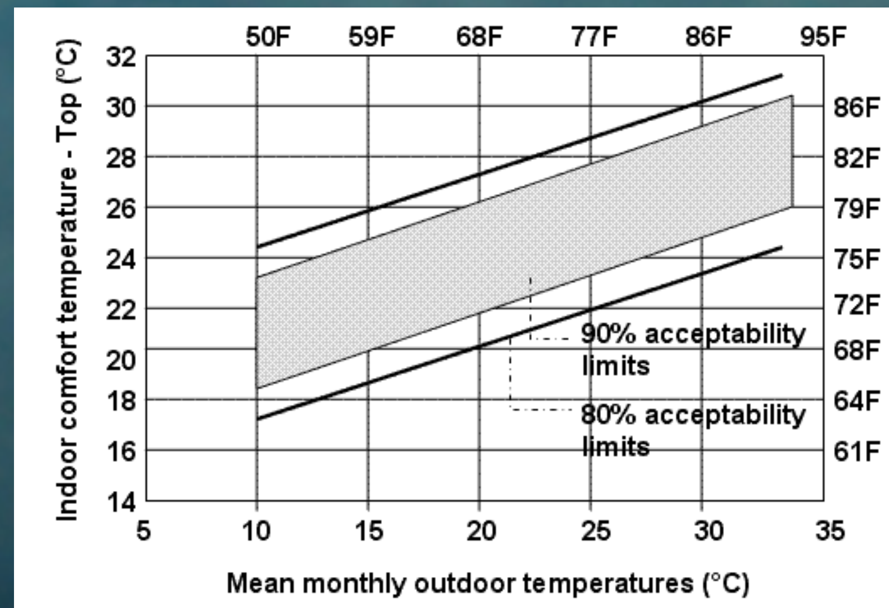
ASHRAE 55-2004 : Comfort Standard

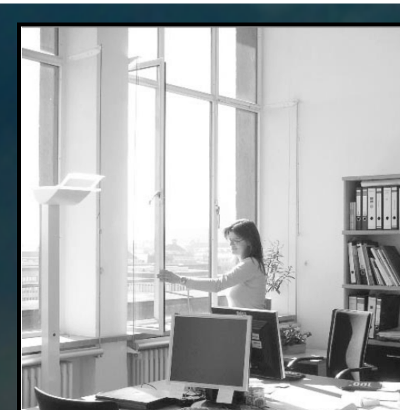
"static"   HVAC standard





adaptive NV standard

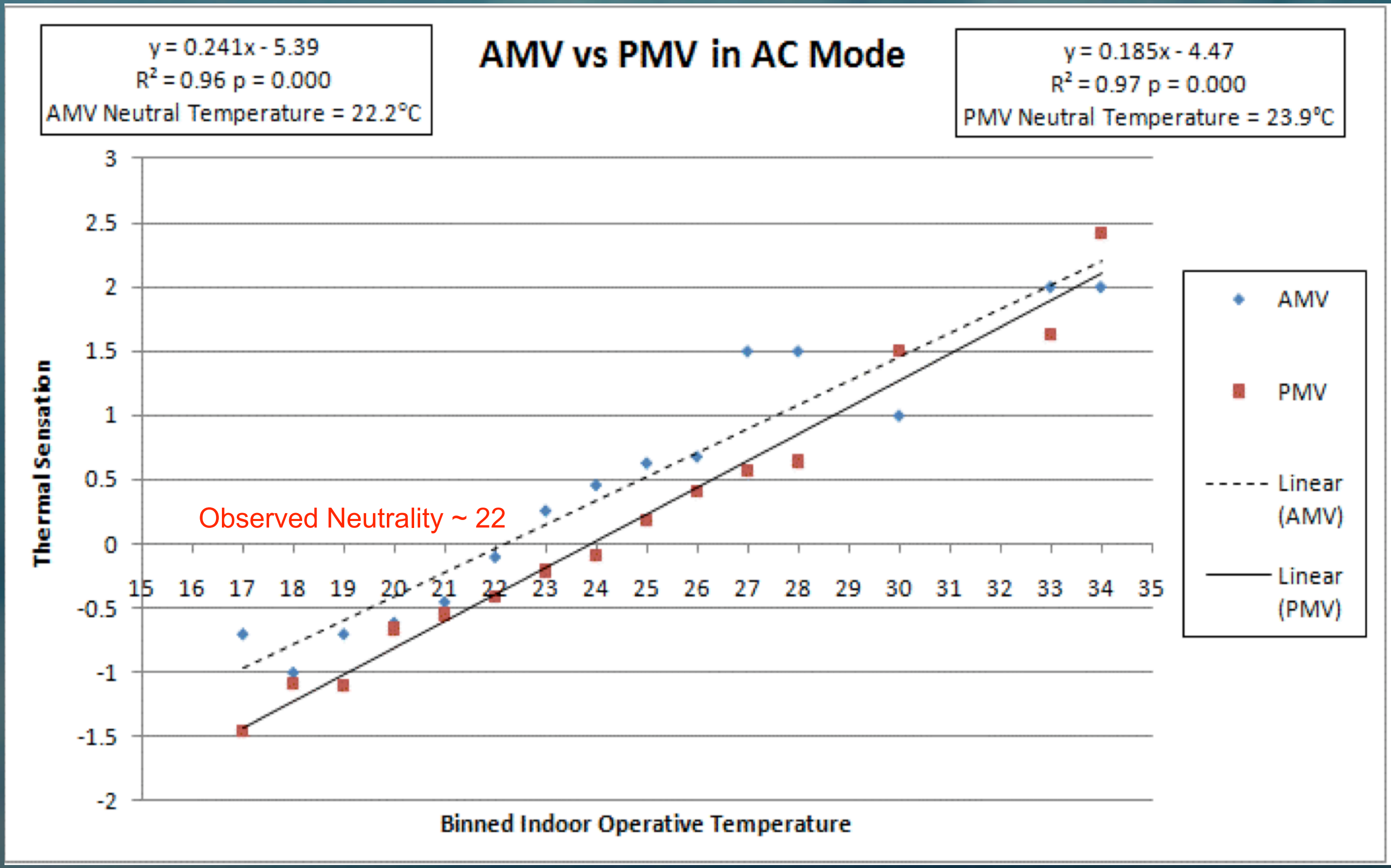




Differences Between CEN and ASHRAE Adaptive Comfort Standards

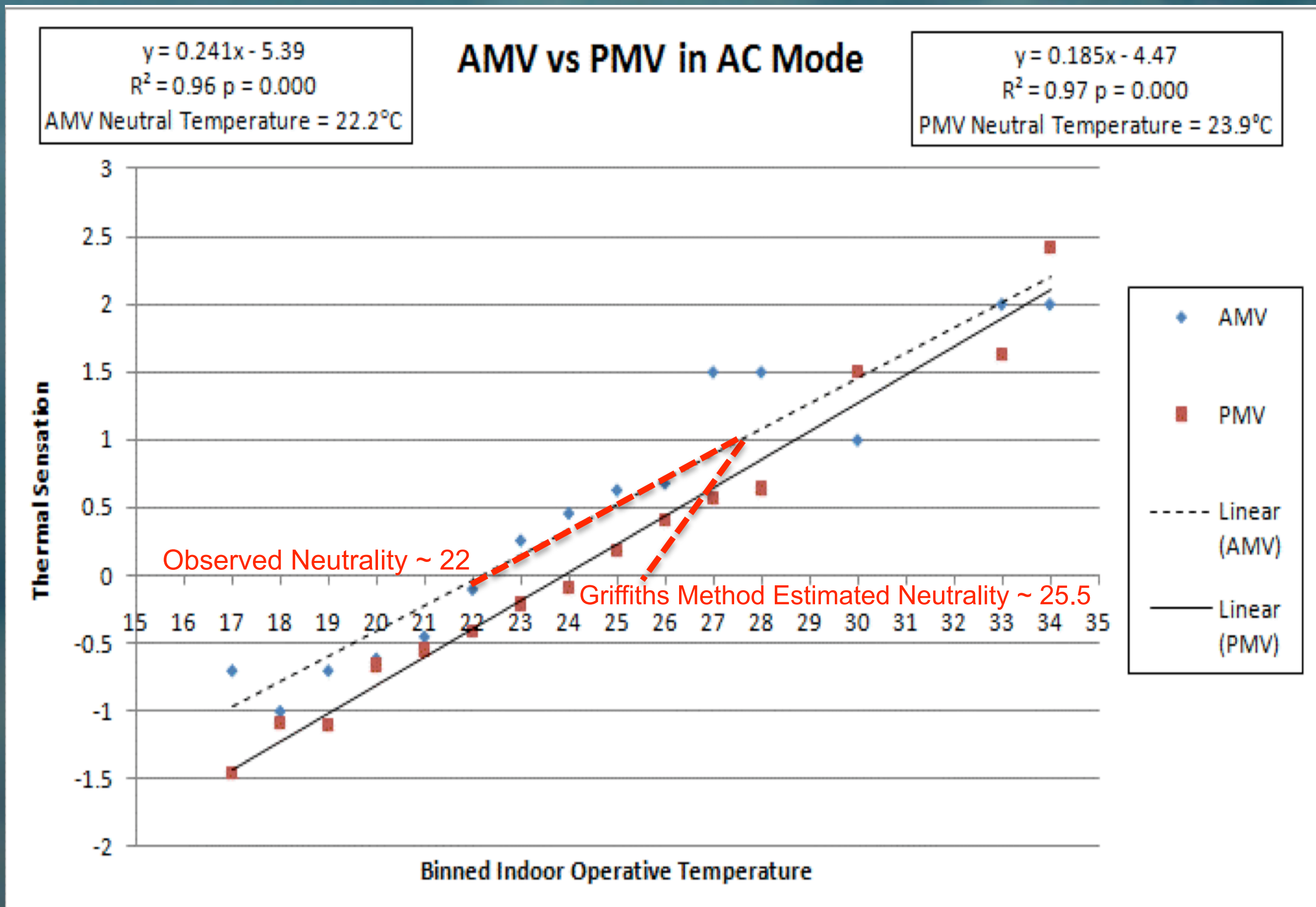
ASHRAE Standard 55-2004 (2010)	CEN Standard EN15252-2007
Geographic/climatic/cultural origins of data – worldwide (RP-884 d'base)	**Geographic/climatic/cultural** origins of data – western Europe (SCATS d'base)
Size of the database – ~ 9,000 out of 21,000 questionnaires 36 out of 160 buildings	**Size** of the database – ~ 1,500 questionnaires in 26 offices
Scope of applicability – naturally ventilated bldgs w/o mech. Cooling (precludes mixed-mode)	**Scope** of applicability – any building in "free running" mode (includes mixed-mode)
Method of deriving **neutrality** – regression of observed comfort votes on observed indoor temperatures for each ***building***	Method of deriving **neutrality** – Griffiths' extrapolation from observed sensation for each ***person*** to hypothetical neutrality by assuming 1 sensation category = 2^{o}C
Representation of **outdoor climate** – Mean monthly outdoor air temperature	Representation of **outdoor climate** – Exponentially weighted running mean of daily outdoor air temperature (~ week)
Occupancy types: sedentary (< 1.3met)	**Occupancy types:** sedentary (< 1.3met)

ASHRAE 55's method for determining neutrality



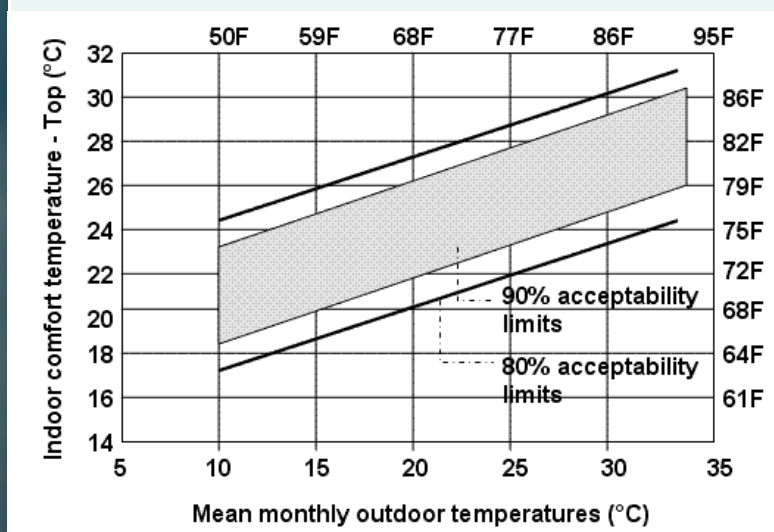
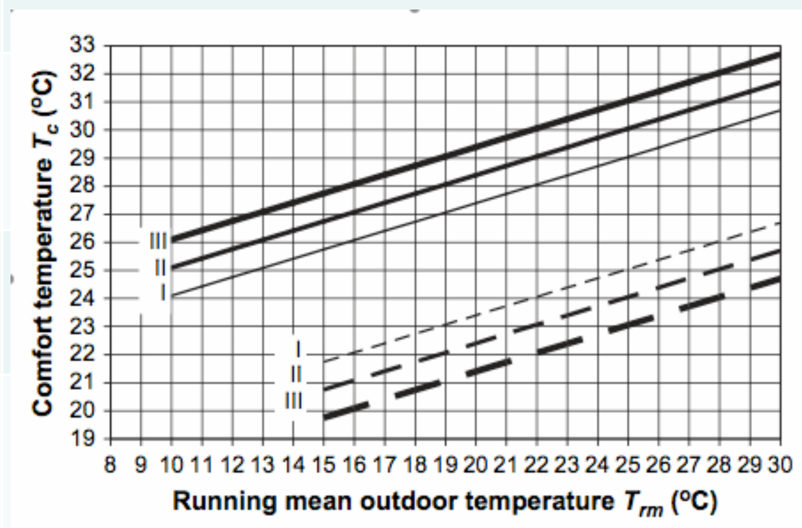
This method estimates neutrality for a group of occupants, surveyed within a single building over a couple of weeks. Neutrality is an ***observed*** parameter for the building, based on **A**ctual **M**ean **V**otes (thermal sensations)

EN15251's method for determining neutrality

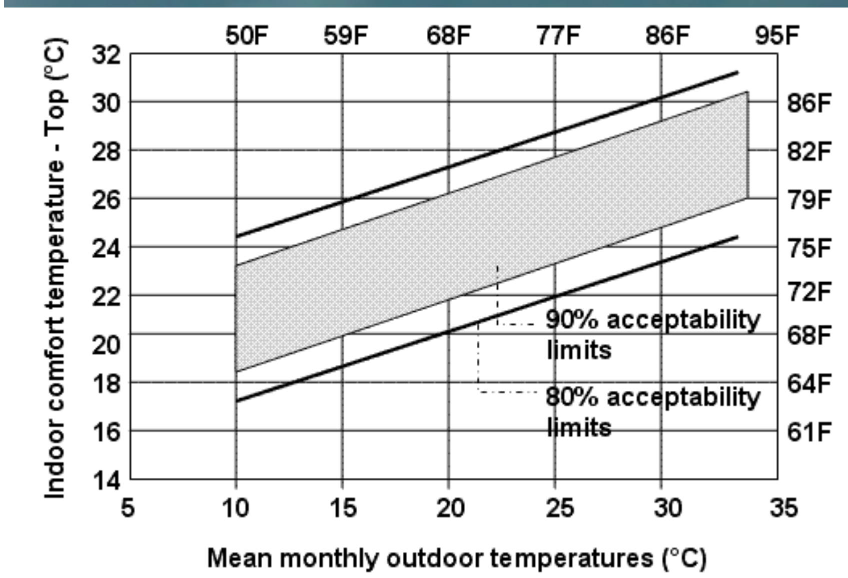


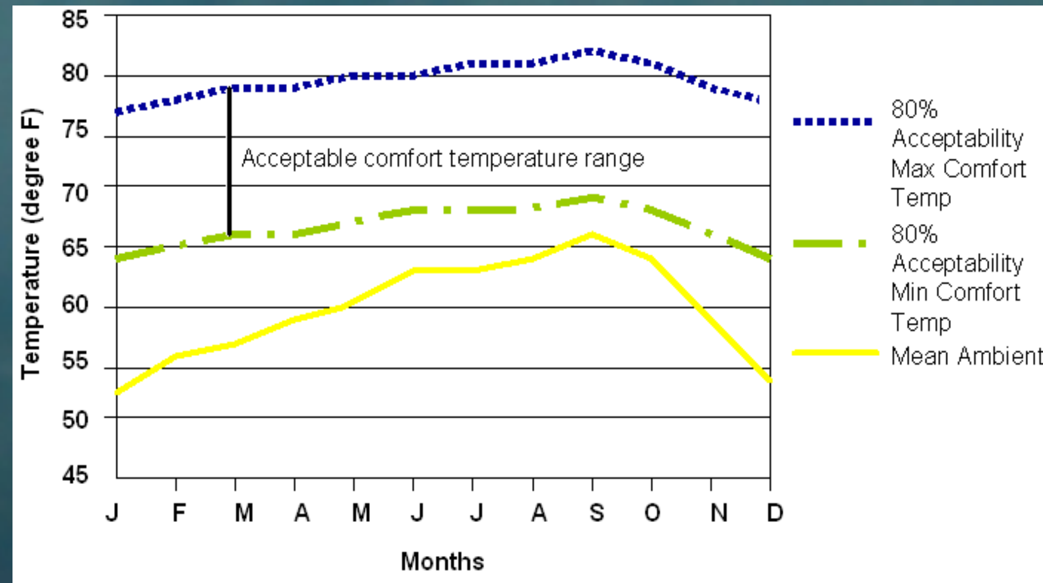
Comparison of observed neutrality (ASHRAE 55) against neutrality estimated from a sensation vote of +1 using the Griffiths Method (EN15251)

Similarities Between CEN and ASHRAE Adaptive Comfort Standards

ASHRAE Standard 55-2004	CEN Standard EN15252-2007
$T_{comf} = 0.31\ T_{outdoor} + 17.8$	$T_{comf} = 0.33\ T_{outdoor} + 18.8$
	

Application of the ASHRAE 55-2010 Adaptive Comfort Standard to San Francisco's climate





From McConahey, E., P. Haves and T. Christ (2002)

Upper 80% acceptability limit (°C) = 0.31 (mean outdoor monthly air temperature) + 21.3
Upper 80% acceptability limit (°F) = 0.31 (mean outdoor monthly air temperature) + 60.5

Lower 80% acceptability limit (°C) = 0.31 (mean outdoor monthly air temperature) + 14.3
Lower 80% acceptability limit (°F) = 0.31 (mean outdoor monthly air temperature) + 47.9

The San Francisco Federal Building, 2008
(source: www.structurae.de photographer: Nicolas Janberg)

Implementing Adaptive Comfort in Building Simulation

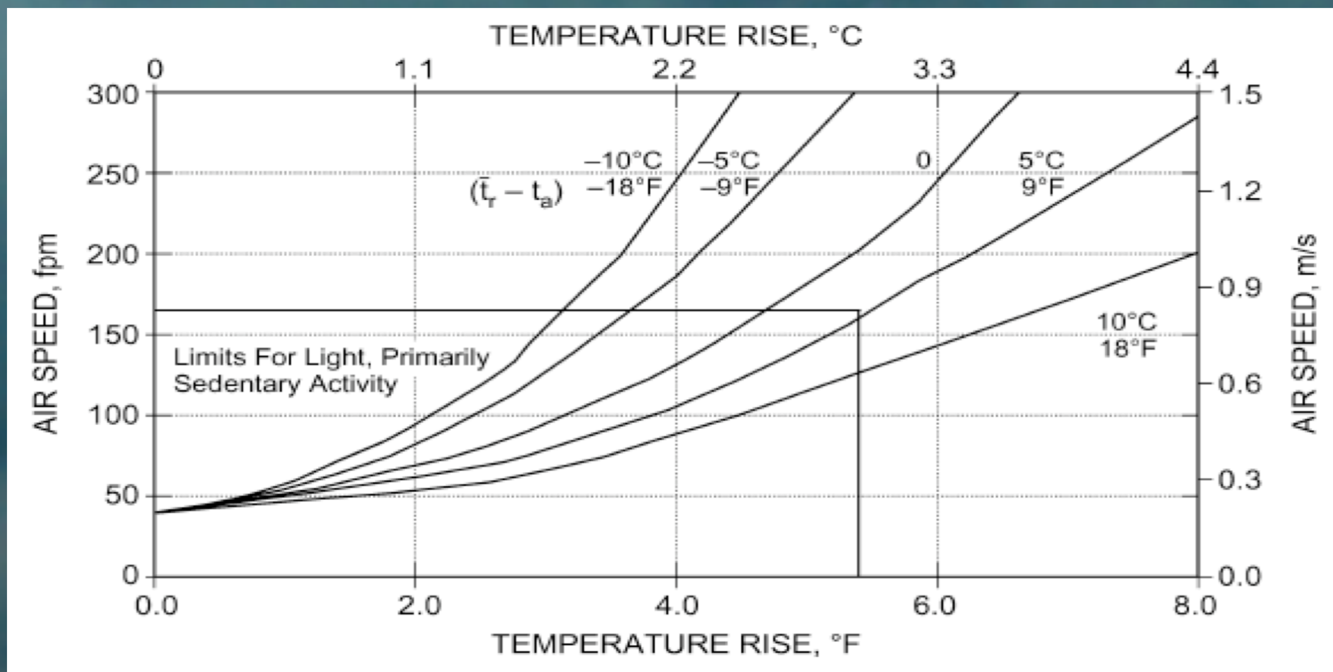
- The x-variable used to generate the ASHRAE 55 adaptive equations is a *mean monthly outdoor air temperature*.
- This can be a climatic mean usually based on the past 20 years, or even *future climatic mean* for say 2030 or 2050, as predicted by GCMs
- In the case of a TMY file there is no logical reason why the x-variable can't be a *running 30-day mean* outdoor temperature.
- Extrapolating from *commercial* buildings to *residential* buildings?
- *Exceedance:*
  - *Duration (% of occupied hours)*
  - *Duration and Intensity (degree hours)*

Future Developments in ASHRAE Standard 55
(Las Vegas ASHRAE SSPC-55 Jan 2011)

Extension of the Adaptive Comfort Limits With Increased Airspeeds in the Occupied Zone

Richard de Dear, Ed Arens, Hui Zhang, Gail Brager

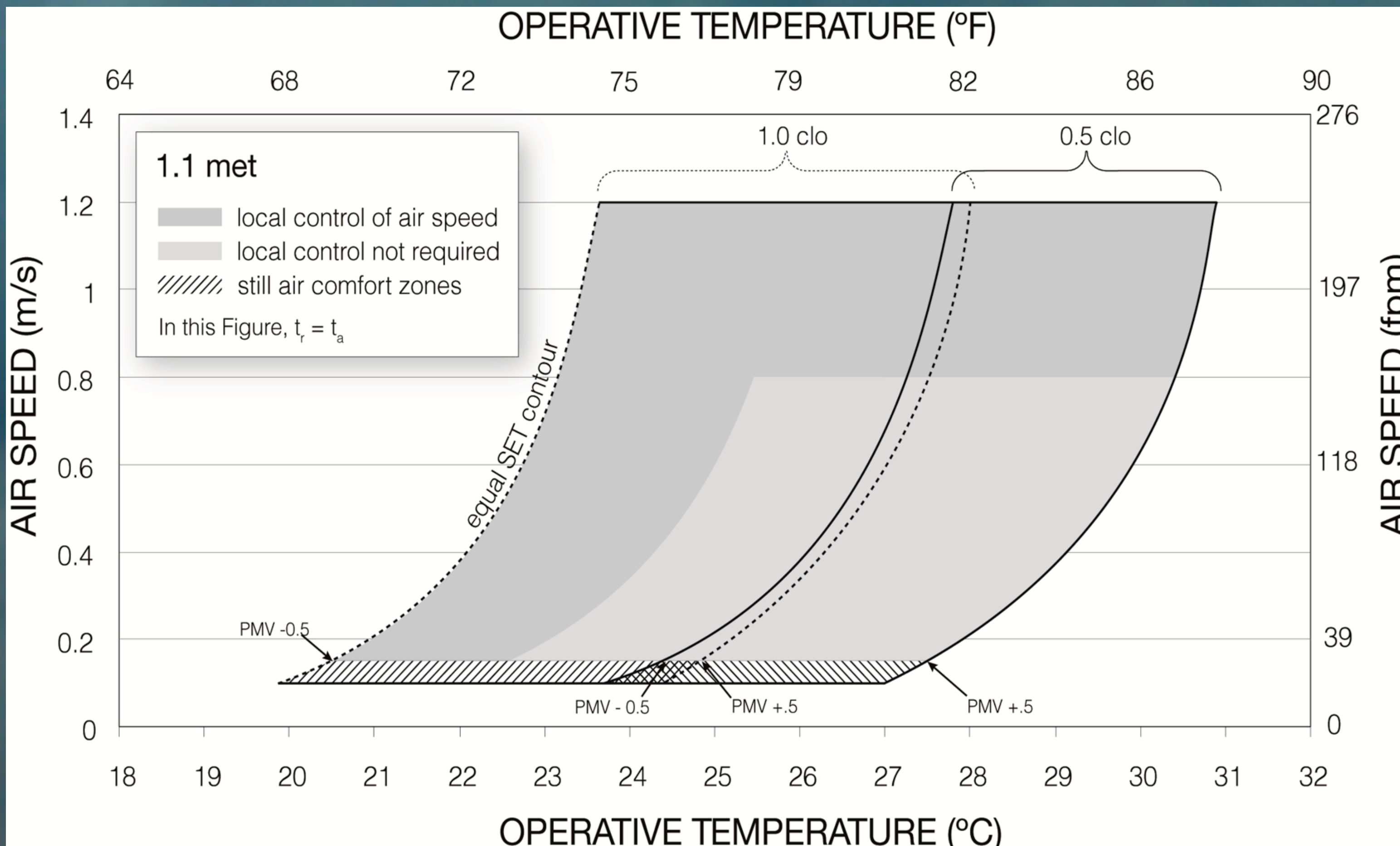
Increased Airspeed has Long Been Used in Standard 55 to Offset Elevated Temperatures in Mechanically Controlled Indoor Climates



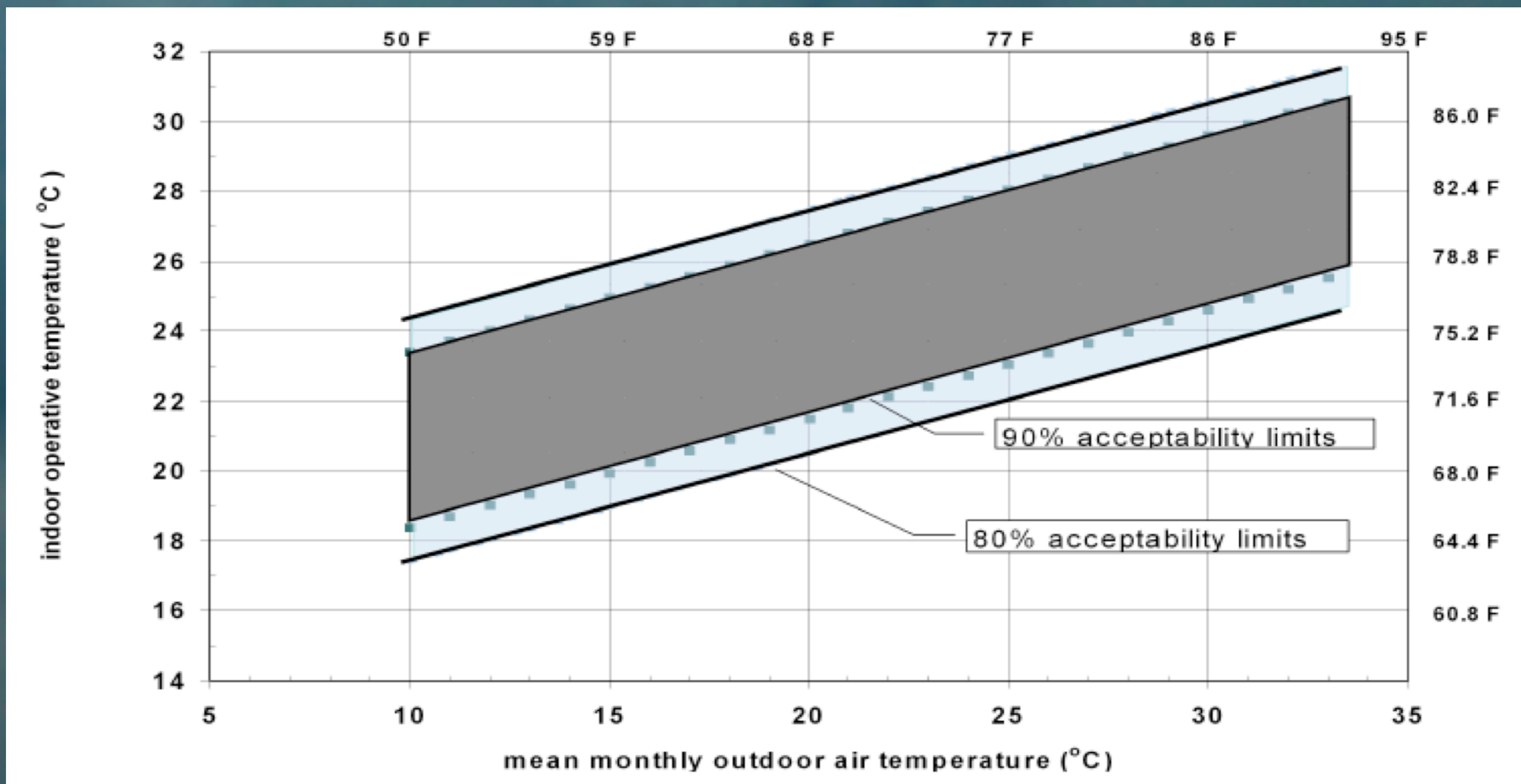
The reference point for these curves is 0.20 m/s (40 fpm). The figure applies to a lightly clothed person (clothing insulation between 0.5 clo and 0.7 clo) who is engaged in near sedentary physical activity (metabolic rates between 1.0 met and 1.3 met).

The curves are generated by the SET thermophysiological model (2-node)

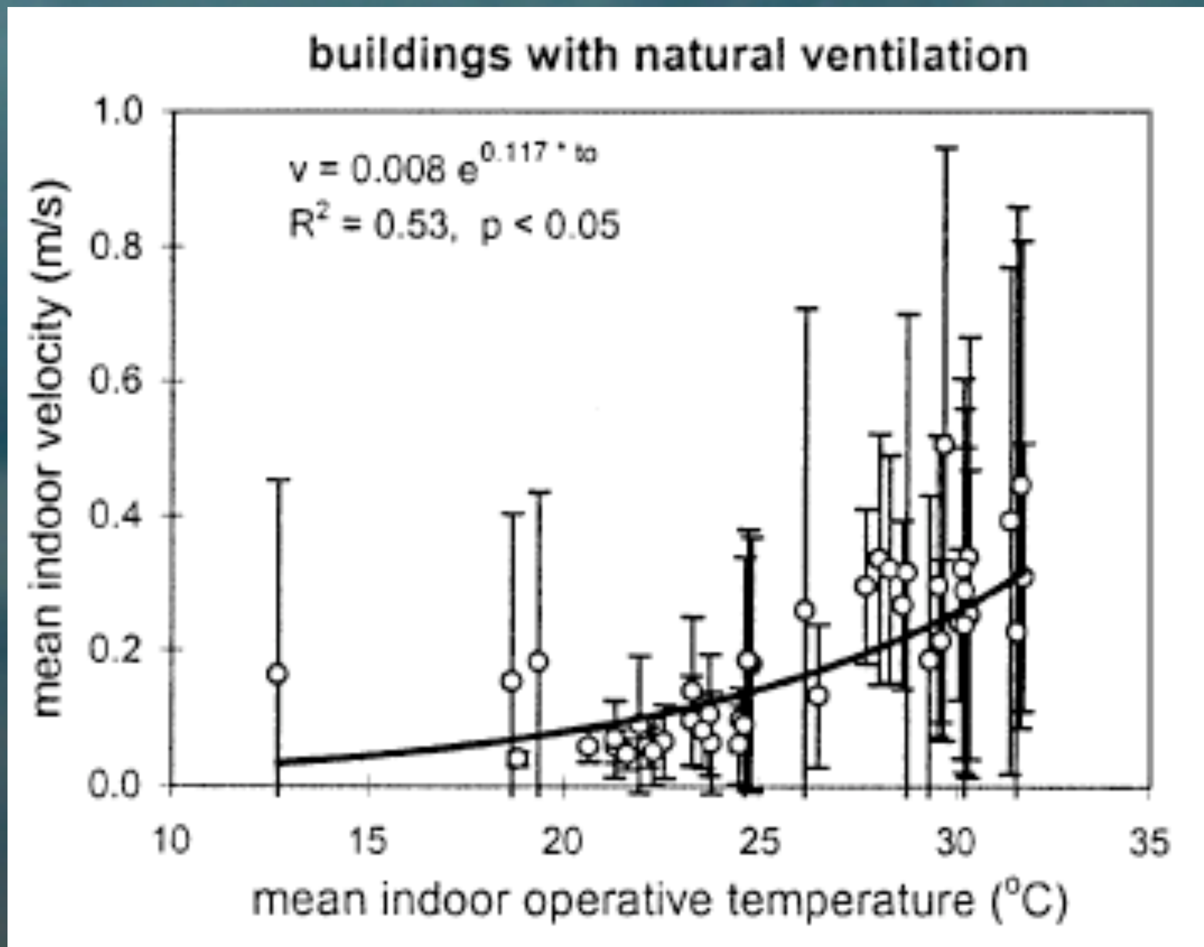
Increased Airspeed has Long Been Used in Std 55 to Offset Elevated Temperatures



This Proposal Extends the Adaptive Temperature Limits With Increased Airspeed



The adaptive comfort standard already includes increasing airspeeds, but only to 0.3m/s (59 fpm)



But the cooling effect of increased airspeed depends on the temperature, the clo level and the metabolic rate

Common SET (C) values at 1.1 met 50% RH	23.1				24.7				26.1				27.7				28.7			
Clo levels	0.4	0.5	0.6	0.7	0.4	0.5	0.6	0.7	0.4	0.5	0.6	0.7	0.4	0.5	0.5	0.7	0.4	0.5	0.5	0.7
T_{op} (C) at 0.3m/s, base case, 80% boundary	25.8	25.0	24.2	23.4	27.2	26.5	25.7	25.0	28.7	28	27.2	26.5	30.3	29.5	28.8	28.1	31.2	30.5	30.5	29.1
T_{op} (C) at 0.6 m/s, and ΔT_{op}	27.0	26.2	25.4	24.6	28.4	27.6	26.8	26.1	30.0	29.2	28.4	27.6	31.6	30.8	30.0	29.3	32.5	31.8	31.75	30.3
T_{op} (C) at 0.9 m/s, and ΔT_{op}	27.6	26.8	26.0	25.2	29.0	28.2	27.4	26.6	30.6	29.8	29.0	28.2	32.2	31.4	30.6	29.8	33.1	32.4	32.4	30.8
T_{op} (C) at 1.2 m/s, and ΔT_{op}	28.0	27.2	26.4	25.6	29.4	28.6	27.8	27.0	31.0	30.2	29.4	28.6	32.6	31.8	31.0	30.2	33.5	32.7	32.7	31.2
ΔT_{op} (C) for an increase in airspeed from 0.3 to 1.2m/s	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	**2.1**	**2.1**	**2.0**	**2.3**	**2.2**	**2.2**	**2.1**	**2.3**	**2.3**	**2.2**	**2.1**	**2.3**	**2.2**	**2.2**	**2.1**

SSPC-55's Approved Text to be Inserted in the Standard

Figure 5.3 includes the effects of people's indoor air speed adaptation in warm climates, up to 0.3 m/s (59 fpm) in operative temperatures warmer than 25°C (77 °F). In naturally conditioned spaces where mean air speeds within the occupied zone exceed 0.3 m/s (59 fpm), the upper acceptability temperature limits in Figure 5.3 are increased by the corresponding Δt_o in Table 5.3, which is based on equal SET values as illustrated in Section 5.2.3.2. For example, increasing mean air speed within the occupied zone from 0.3 m/s (59 fpm) to 0.6 m/s (118 fpm) increases the upper acceptable temperature limits in Figure 5.3 by a Δt_o of 1.2°C (2.2°F). These adjustments to the upper acceptability temperature limits apply only at $t_o > 25°C$ (77 °F) in which the occupants are engaged in near sedentary physical activity (with metabolic rates between 1.0 met and 1.3met).

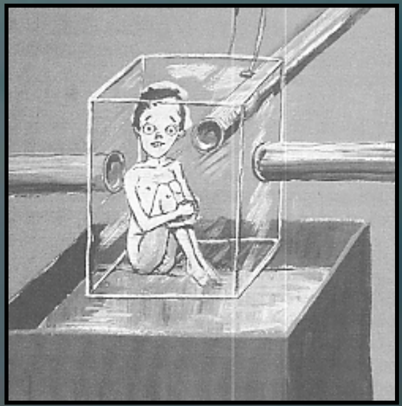
TABLE 5.3

Increases in Acceptable Operative Temperature Limits (Δt_o) in the Adaptive Comfort Standard (Figure 5.3) Resulting from Increasing Mean Air Speed Above 0.3 m/s (59 fpm).

Mean Air Speed 0.6 m/s (118 fpm)	Mean Air Speed 0.9 m/s (177 fpm)	Mean Air Speed 1.2 m/s (236 fpm)
1.2°C (2.2°F)	1.8°C (3.2°F)	2.2°C (4.0°F)

Conclusions

- In rapidly *developing economies* the key challenge is to leap-frog over the "static" comfort model (*PMV/PPD*) and design to the adaptive approach where and when feasible.
- In developed economies the key challenge lies in retrofitting adaptive comfort into existing buildings. The term "*adaptive HVAC*" has already been coined, but this implies "weaning" occupants off tightly regulated (static) indoor climates.
- Perhaps the final frontier for adaptive thermal comfort researchers will be the "*engineering of building occupants' attitudes and expectations*"



Green buildings need green occupants!

Thank you for your attention