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Thermal adaptation in the built environment: a literature review

Gail S. Brager [a,*], Richard J. de Dear [b]
[a] Center for Environmental Design Research, University of California, Berkeley, CA 94720-1839, USA
[b] Climatic Impacts Centre, Macquarie University, Sydney, NSW 2109, Australia

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Abstract

This paper presents the results of an extensive literature review on the topic of thermal adaptation in the built environment. The adaptive approach to modeling thermal comfort acknowledges that thermal perception in 'real world' settings is influenced by the complexities of past thermal history and cultural and technical practices. An important premise of the adaptive model is that the person is no longer a passive recipient of the given thermal environment, but instead is an active agent interacting with the person–environment system via multiple feedback loops. Thermal adaptation can be attributed to three different processes—behavioral adjustment, physiological acclimatization and psychological habituation or expectation. Both climate chamber and field evidence indicates that the slower process of acclimatization is not so relevant to thermal adaptation in the relatively moderate conditions found in buildings, whereas behavioral adjustment and expectation have a much greater influence. One of the most important findings from our review of field evidence was the distinction between thermal comfort responses in air-conditioned vs. naturally ventilated buildings, most likely resulting from a combination of past thermal history in the buildings and differences in levels of perceived control. © 1998 Published by Elsevier Science S.A.

Keywords: Adaptation; Natural ventilation; Individual control

1. Introduction

What constitutes a 'comfortable' thermal environment? The answer to this deceptively simple question has profound implications for the way we design and operate buildings, the amount of energy required to heat and cool them and the resulting impact on the quality of both the natural and built environments. For example, traditional lifestyles in tropical regions can inspire a distinctive climate-responsive architecture, where buildings are naturally ventilated and not only consume less energy, but give occupants a sense of comfort, delight and connection to their climate and culture [1]. Such buildings, however, are giving way to sealed glass towers and an increased reliance on mechanical cooling, which in turn is changing building occupants' expectations, desires and behavioral patterns related to air conditioning [2–6]. A key question addressed in this paper is whether occupants in these different building types would all define 'comfort' in the same way.

Existing standards which prescribe 'ideal' conditions for thermal comfort are based on a heat balance model of the human body and are derived from extensive experiments in climate chambers, conducted primarily with university students in mid-latitude climate regions [7,8]. Although these standards were initially developed for centralized HVAC-controlled buildings, it is often suggested that they are universally applicable across all building types, climates and populations [9,10]. In practice, however, they provide little guidance for the design and operation of buildings that are either naturally ventilated, or provide occupants with other means of individual control over their thermal environment. We join other researchers, therefore, in challenging this assumption of universal applicability and would argue that a strict reliance on laboratory-based comfort standards ignores important contextual influences that can attenuate responses to a given set of thermal conditions. Perhaps the single biggest issue in this debate remains the applicability of standards in buildings which are not air conditioned at all. An entire issue of *Energy and Buildings* was devoted to the social and cultural aspects of cooling, including the variation among people in the perceived need or desire for air conditioning [11]. While the 'comfort zone' might be an appropriate design goal for a deterministic HVAC control system, its relevance to naturally ventilated buildings where conditions are inherently much more variable is questionable [12,13]. This was recognized by Givoni [14], who revised his already notable work on the building bioclimatic chart to account for the notion that people living in unconditioned buildings would

* Corresponding author.

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become accustomed to and grow to accept higher temperature or humidities. To do this in a systematic way, however, requires a fundamental shift in the way we view the relationship between people and their thermal environment.

An alternative to conventional comfort theory embraces the notion that people play an instrumental role in creating their own thermal preferences through the way they interact with the environment, or modify their own behavior, or gradually adapt their expectations to match the thermal environment. Interest and research into this 'adaptive' theory of thermal comfort first began in the mid-70's in response to the oil-shocks and has recently regained momentum due to increasing concerns over human impact on the global climatic environment. Allowing people greater control over their own indoor environment and allowing temperatures to more closely track patterns in outdoor climate, can have potentially significant and positive impacts on both improving comfort and reducing energy consumption [15], as well as altering the way we design and operate buildings.

This paper presents the results of an extensive literature review on the topic of thermal adaptation in the built environment, with a focus on air-conditioned vs. naturally ventilated buildings. After a brief discussion of conventional heat balance models, we describe a conceptual model of thermal adaptation, present a wide range of both climate chamber and field evidence for thermal adaptation of building occupants and discuss the potential applications of an adaptive thermal comfort theory in terms of predictive modeling, building design, control algorithms and standards.

2. Defining the adaptive process

2.1. *The heat balance model*

In contemporary thermal comfort research there appears to be an irreconcilable split between heat balance and adaptive modeling approaches. Heat balance models, also referred to as the 'static' or 'constancy' models, were the basis of the early pioneering work of Gagge et al. [16,17] and Fanger [18] and have been adopted into current standards that prescribe acceptable conditions for thermal comfort [7,8]. Heat balance models view the person as a passive recipient of thermal stimuli and are premised on the assumption that the effects of a given thermal environment are mediated exclusively by the physics of heat and mass exchanges between body and environment. The maintenance of a constant internal body temperature necessitates some physiological responses proportional to the thermal imbalance and it is generally assumed that thermal sensations (hot–warm–cool–cold) are proportional to the magnitude of these responses, as measured by mean skin temperature and latent heat loss or wettedness due to sweating [19]. The deterministic logic underpinning the heat balance comfort model is:

physics $\Rightarrow$ physiology $\Rightarrow$ subjective discomfort

These models are based on extensive and rigorous laboratory experiments and yield fairly consistent, reproducible results between climate chambers. However, researchers are increasingly questioning whether the simplistic cause-and-effect approach embodied in these laboratory-derived models can be applied, without modification, to describe real-world thermal perception [20–24]. One perceived limitation of the heat balance model, when used as a design tool, is that the user has to anticipate what average clo (clothing insulation) and met (metabolic rate) values might exist in a building which may not have been built. Yet, even when applied to occupied buildings where the crucial input parameters of metabolic rate and clothing insulation can be observed, these models frequently still fail to accurately describe or predict thermal comfort [25–40]. Potential explanations for the wide discrepancies often found between observed and predicted mean thermal sensations can be categorized into the following groups.

2.1.1. *Model inputs*

2.1.1.1. *Estimating insulation of clothing garments or ensembles*

Brager et al. [37] demonstrated that the calculated clothing ensemble insulation value (clo) differs by as much as 20% depending on the source of the tables and algorithms commonly used [7,8,41]. In addition, clothing insulations measured under laboratory conditions with an inanimate thermal manikin may be different than in situ clothing insulation due to factors such as posture, pumping effect, different material fibers, vapor permeability, fiber thermodynamics under transient environmental conditions [42–45].

2.1.1.2. *Accounting for the chair insulation*

The tendency for PMV to overestimate thermal neutralities in many field studies may be due to the systematic omission of the thermal effect that chairs have on their occupants [33,46]. McCullough and Olesen [47] examined the effects of upholstered office furniture on the total thermal insulation of a heated manikin and found that a typical office chair adds approximately 0.15 clo to the value that one gets by simple addition of individual garment values [7,8].

2.1.1.3. *Estimating activity patterns and associated met levels*

Existing field methods for assessing people's activity patterns and then translating them into metabolic rates using standard tables, are perhaps one of the least-developed methods of thermal comfort research. Factors that would influence the assessment of metabolic rate would include the mental stress related to a given task, transient effects of earlier activities, or the vigor with which a given activity is performed [48].

2.1.1.4. Non-uniformities of physical measurements

Field studies often take only spot-measurements of ambient thermal parameters and, if they happen to be slightly separated from the occupant's location in space and/or time, they might not be representative of the indoor microclimate actually experienced by the occupant [44]. This becomes particularly important in rooms with transient or spatially non-uniform thermal conditions as is often the case in passive, or naturally ventilated buildings, or any situations where workers have high levels of environmental control available to them.

2.1.2. Model assumptions—steady-state vs. transient

Static heat balance models are based on experiments in steady-state conditions in the laboratory, whereas conditions in buildings are likely to be much more dynamic, in terms of both the thermal environment and the occupants' activities. (In terms of human ecology, this variance is referred to as ecological valency and ecological potency, respectively [5].) Although more work is needed in this area, examples of preliminary studies suggest that clothing can significantly affect one's response to humidity transients [49] and that cold temperature transients give rise to a strong subjective response compared to warm transients of equal magnitude [50].

2.1.3. Non-thermal factors

Human response to conditions in real buildings may be influenced by a range of complex factors that are not accounted for in the heat balance models. These can include demographics (gender, age, culture, economic status), context (building design, building function, season, climate, semantics), environmental interactions (lighting, acoustics, indoor air quality) and cognition (attitude, preference and expectations) [38,44,51–53]. While the factors that have been tested have been demonstrated time and again to be irrelevant to the comfort responses of subjects in the contrived setting of the climate chamber [54,55], there remains a lingering suspicion in the minds of many researchers and practitioners alike that non-thermal factors cannot be dismissed so easily. For example, it has been suggested that a particularly important influence is the impact of one's perception of control—psychologists have clearly demonstrated that adverse or noxious stimuli are less irritating if the subject perceives she/he has control over them [56–62]. This and other forms of adaptation will be explored throughout this paper.

2.2. A conceptual model of thermal adaptation

Environment and behavior research teaches that one's experience of a place is a multi-variate phenomena and a reflection of the degree to which the place contributes to a person's objectives and expectations [63,64]. In the adaptive approach to modeling thermal comfort, thermal perception is affected by circumstances beyond the physics of the body's heat-balance, such as climatic setting, social conditioning, economic considerations and other contextual factors. The adaptive hypothesis states that one's satisfaction with an indoor climate is achieved by matching the actual thermal environmental conditions prevailing at that point in time and space, with one's thermal expectations of what the indoor climate should be like. These all-important expectations result from a confluence of current and past thermal experiences and cultural and technical practices [21,22,65]. The adaptive model reflects a 'give and take' relationship between the environment and the user, an important premise being that the person is no longer simply a passive recipient of the given thermal environment (a deterministic view more appropriate for a climate chamber experimental subject), but instead is an active agent interacting with and adjusting to the person–environment system via multiple feedback loops [58,59].

The generic term 'adaptation' might broadly be interpreted as the gradual diminution of the organism's response to repeated environmental stimulation and subsumes all processes which building occupants undergo in order to improve the 'fit' of the indoor climate to their personal or collective requirements. Within this broad definition, the literature distinguishes three modes of adaptation [66–70]: (1) behavioral adjustments (personal, environmental, technological, or cultural), (2) physiological (genetic adaptation or acclimatization) and (3) psychological (habituation or expectation).

2.2.1. Behavioral feedback—adjustment

Behavioral adjustment includes all modifications a person might consciously, or unconsciously make, which in turn modify heat and mass fluxes governing the body's thermal balance [71]. We define adjustment in terms of three subcategories: (1) personal adjustment: adjusting to the surroundings by changing personal variables, such as adjusting clothing, activity, posture, eating/drinking hot/cold food or beverages, or moving to a different location; (2) technological or environmental adjustment: modifying the surroundings themselves, when control is available, such as opening/closing windows or shades, turning on fans or heating, blocking air diffusers, or operating other HVAC controls, etc.; and (3) cultural adjustments, including scheduling activities, siestas, adapting dress codes, etc.

Behavioral adjustment of the body's heat-balance probably offers the greatest opportunity for people to play an active role in maintaining their own comfort. Chatonnet and Cabanac [72] stated that "behavioral thermoregulation is well-developed in man and becomes preponderant and tends to supplant other forms of thermoregulation".

The heat balance model partially accounts for behavioral adjustment, but in a linear way by using only as inputs those parameters affected by personal adjustment and environmental interventions (i.e., clothing, metabolic rate, air movement, etc.) In the adaptive view of thermal comfort, however, behavioral adjustment represents an immediate and conscious feedback link, where the sense of discomfort or dissatisfaction is not only the outcome but also serves as the starting point, initiating the adaptive response. Simply stated, if a person is uncomfortable, or expects to become so, this is a signal to take corrective action.

Behavioral adaptation operates across several time scales. Cutaneous thermoreceptors provide almost instantaneous neural information about sudden changes in the thermal environment, as experienced, for example, when crossing the indoor/outdoor threshold, thus enabling clothing adjustments and other behavioral adaptations to be effected well in advance of any significant alteration in the body's heat balance. While very little research has been published on adaptive time lags, a notable exception is a study by Humphreys [73] on clothing adjustments at the seasonal and synoptic weather time scales. He was able to statistically relate clothing insulation levels on any given day to an exponentially weighted moving average of outdoor temperatures on the days leading up to and including the day in question. It was suggested that the half-life for daytime clothing regulation was of the order of 20 h in the UK.

The extent to which buildings provide occupants with scope for adaptive interventions has been described both in terms of 'adaptive opportunity' [53] and 'adaptive constraints' [23,74]. Examples of each can be categorized as follows:

(a) Climate. Buildings in mild climates will tend to afford their occupants greater adaptive opportunities, compared to buildings in harsh or extreme climates that might need to present a more exclusive barrier to the elements.

(b) Economics. Both the initial and operating costs of thermal environmental control may be an acceptable part of clients' budgets in developed countries, but often exceed owners' resources in many developing countries.

(c) Building design. Opportunities and constraints can relate to attributes of the building envelope (What is the placement and size of windows? Are they operable? Are solar control devices available?); interior layout (How far are occupants placed away from such windows? Is the floor plan individual office cells or open-plan bureau landschaft?); or climate control system (Is the HVAC system centralized? Are task conditioning controls available at each workstation or within small zones?).

(d) Organizational and social customs. This category refers either to conditions prevailing within the building (Is there a strict or casual dress code? Are employees bound to a single workstation for the entire working day?), or to requirements imposed from the outside (government energy guidelines, greenhouse gas emission quotas or targets that limit our freedom to behaviorally thermoregulate).

The concept of adaptive opportunity helps to differentiate those buildings in which a deterministic relationship between the thermal environment and human response is operating and those in which an adaptive feedback loop is fully developed and operational. Adaptive opportunity can be thought of as a continuum—at one extreme is the climate chamber in which subjects are instructed what to wear and what activities they are to perform while an external agent, the researcher, determines the temperature, humidity and air flow regime they are to experience for the duration of the experiment. At the other extreme we can place the single-occupant room in which clothing and activity patterns are discretionary and environmental controls cover the full range of possibilities from operable windows through to task-ambient air conditioning. The ultimate efficacy of any form of adaptive control would ideally be evaluated in terms of *available control* vs. *exercised* control vs. *perceived* control [60,61]. But regardless of whether it is placebo or real, there seems little dispute that the issue of personal and environmental control is central to thermal comfort and acceptability.

2.2.2. *Physiological feedback—acclimatization*

The most comprehensive definition of physiological adaptation would include all of the changes in the physiological responses which result from exposure to thermal environmental factors and which lead to a gradual diminution in the strain induced by such exposure. Physiological adaptation can be broken down into at least two subcategories: (1) genetic adaptation—alterations which have become part of the genetic heritage of an individual or group of people, developing at time scales beyond that of an individual's lifetime and (2) acclimation or acclimatization (used interchangeably here)-changes in the settings of the physiological thermoregulation system over a period of days or weeks, in response to exposure to single or a combination of thermal environmental stressors.

Physiological acclimatization is mediated by the autonomic nervous system and directly affects the physiological thermoregulation setpoints. The heat balance models do not recognize this form of adaptation, however, assuming these setpoints to be fixed. A detailed review of the thermophysiological literature on acclimatization is beyond the scope of this paper, suffice to say that acclimatization to cold stress is primarily associated with maintenance of warmer skin temperatures and increased heat production, although it is not clear to what extent the increased metabolic rate can occur in the absence of shivering [75]. Otherwise, adaptation to the cold is primarily behavioral [70]. The evidence for physiological acclimatization is more thoroughly documented for heat exposure, particularly for high temperature environments and/or for subjects working in the heat [68,69,76–79]. For hot–dry climate zones, the primary physiological response to heat stress, induced by a regime of work in heat, is an increased sweating capacity for a given heat load, be it metabolically or environmentally induced. Other changes related to thermoregulatory sweating include a fall in the setpoint body temperature at which sweating is triggered and a better distribution of sweat over the skin. The heat-acclimatized person also demonstrates a variety of cardiovascular responses such as reduced heart rate, and an increased blood volume and peripheral blood flow compared to their unacclimatized counterpart [79–82]. The picture in hot–humid climates, however, differs significantly [83,84]. In particular, the elevated capacity for sweating seems to be less important in humidity. Thus, while sweat secretion in the humid acclimatized subject is initiated at a core temperature lower than that for the unacclimatized subject, the shortfall in body heat dissipation in the humid condition appears to be taken up by increased dry heat losses resulting from increased peripheral blood flow and elevated skin temperature.

Experiments with daily work-in-heat regimes or hyperthermic suits demonstrated that acclimatization to heat begins on the first day of exposure and progresses rapidly to full development by the third or fourth day, providing the heat exposures are sufficiently severe to elevate core temperatures [78,80]. Longer periods are required for cold acclimatization, or for passive exposures to heat in the course of normal day-to-day sedentary activity [76]. For example, Wyndham [82] reports that passive exposures to the normal course of the seasons in South Africa induced definite signs of at least partial acclimatization. The time scales of interest for office workers, therefore, may be of the order of weeks to months.

2.2.3. Psychological feedback—habituation and expectation

Psychological adaptation encompasses the effects of cognitive and cultural variables and describes the extent to which habituation and expectation alter one's perception of and reaction to sensory information. This notion, also sometimes referred to as perceptual adaptation [20], is described in psychophysics as repeated or chronic exposure to an environmental stressor leading to a diminution of the evoked sensation's intensity [75,85]. The static heat balance model has no ability to account for this influence, instead assuming an unchanging relationship between physiological strain, thermal sensation and associated discomfort. On the other hand, the adaptive model recognizes the potential for a feedback loop where one's past and current thermal experiences, with both the indoor and outdoor climate, can directly affect one's thermal response and cognitive assessment of acceptability.

The concept of habituation and expectation has been most clearly elaborated under the banner 'adaptation-level theory', which introduces the notion of optimal levels of stimulation, or adaptation levels. These optimal adaptation levels are established as functions of past exposure and act as benchmarks or norms for environmental evaluations [71,86–88]. While a thorough review of research on the *general* nature of perception and its relationship to environmental stimuli, memory and cognition and contextual factors is far beyond the scope of this paper, the vast literature of environmental psychology can still offer insights into the specifics of *thermal* perception in real buildings [56,62–65,89,90].

The role of expectation in thermal comfort research was acknowledged in the earlier work of McIntyre [91], who stated that "a person's reaction to a temperature which is less than perfect will depend very much on his expectations, personality and what else he is doing at the time." Although the least studied of the three adaptive mechanisms, psychological adaptation might actually play the most significant role in explaining the differences in observed and predicted thermal sensations and acceptability, particularly in light of different environmental contexts such as the laboratory vs. home vs. office, or when comparing responses in air-conditioned vs. naturally ventilated buildings [27,31,34,35,39,40]

Unfortunately this literature review was unable to find reference to any research on the time scales of psychological adaptive response, probably for the simple reason that no researchers have attempted to disentangle psychological from other thermal adaptive processes. However, anecdotal evidence suggests that building occupants become accustomed to levels of warmth prevailing within buildings on time scales of weeks to months. These scales translate into synoptic and seasonal processes operating in the outdoor atmospheric environment.

3. Climate chamber evidence for adaptation to climate

While climate chambers lack the realism of an actual building and are unsuitable for longitudinal studies, they are nonetheless useful tools due to their high degree of control and reproducibility. Therefore, a thorough examination of people's thermal adaptation should consider evidence from *both* the field and the laboratory. A research design for climate-chamber experiments known as the 'preferred temperature method' [91] has been applied by various researchers to the questions raised by the adaptive hypothesis. This method is ideally suited to testing adaptive feedbacks insofar as the environmental temperature within the chamber is directly controlled by its single occupant, the subject. What follows is a summary of some of the more pertinent results.

Using a climate chamber, Fanger investigated the effects of differing cold climatic experiences and by implication, adaptive states, on thermal comfort responses by comparing the temperature preferences of three groups of Danish subjects—regular college students [92], winter swimmers [93] and meat packers from a refrigerated storeroom [93]. Using the same experimental procedures (standard 0.6 clo ensemble, string chair, 2.5-h exposure), all three groups were found to have the same preferred temperature of about 25.5°C.

To examine the effects of acclimatization in the moderate heat stress range, Fanger [94] recruited a sample of 16 long-term inhabitants of the tropics shortly after their arrival in Copenhagen. The same procedure as described above was followed and the result, again, was that temperature preferences were not significantly different from 25.5°C. Acknowledging the limited 'shelf-life' of the physiological effects of heat acclimatization, de Dear et al. [95] replicated Fanger's tropical experiment on location in Singapore (lat 1°N) using a sample of 32 college students from that country's national university. Again, temperature preferences turned out not to be significantly different from those of Fanger's benchmark Danish subjects.

Chung and Tong [96] conducted yet another laboratory study that produced no evidence of acclimatization. Using a climate chamber in Hong Kong, 134 young Chinese wore 0.6 clo uniforms and maintained sedentary activity during a 3-h exposure. Although the protocol was slightly different than the previous studies (a matrix of constant temperature tests were conducted, rather than the preferred temperature method), the results were not significantly different, with a mean neutral temperature of 24.9°C.

Gonzalez [97] studied the role of short-term natural heat acclimatization during a five-day heat wave in New Haven Connecticut, during which daily maxima ranged between 32°C and 37°C concurrently with 88 to 90% rh. For lightly exercising young male subjects (116 W m^{-2}), there was a discernible increase in preferred temperature (as assessed by a rating scale) after the heat wave. However, there were no statistically significant differences in thermal comfort or acceptability responses of resting subjects between the before- and after-heat-wave tests.

Interestingly, the only significant departure from this picture of overall consistency in chamber research results has been an as yet unpublished PhD thesis from the University of London.[1] As part of this study, Malay subjects were tested in climate chambers in both Malaysia and London and results cited by Humphreys [23] suggest that the hot and humid climatic context of the Malay peninsula was responsible for a three-degree elevation of temperature preference (28.7°C) compared to what was found in the London climate chamber (25.7°C). These results are quite perplexing, however, insofar as the same ethnic mix of subjects with exactly the same thermal histories and experiences were represented in the previously described de Dear et al. [95] chamber study in Singapore (at the tip of the Malay peninsula and climatologically no different to Malaysia). As noted earlier, the temperature preferences in Singapore's climate chamber were consistent with all the other cited studies and are even comparable to the results in the London climate chamber. Without further information about their experimental methods, we can offer no explanation for these unpublished anomalous findings from the Malaysian climate chamber study.

To summarize, on the basis of experimental evidence published to date, subjective discomfort and thermal acceptability under conditions most typically encountered in residences and office buildings, with resting or lightly active building occupants, appear unlikely to be affected by the physiological processes of acclimatization.

4. Field evidence for adaptation

While chamber studies have the advantage of carefully controlled conditions, field studies are best used for assessing the potential impacts of behavioral or psychological adaptations as they occur in 'real-world' settings. This paper examines these impacts by summarizing and comparing the published results of field studies conducted in a cross-section of climates. The authors have conducted new analysis on the cumulative raw data from many of these studies and this is reported elsewhere [98,99].

The extent to which a field study can determine precisely what adaptation mechanisms are taking place depends on the level of detail in both the subjective questionnaires and, more importantly, the physical measurements. Three broad classes of thermal comfort field investigation can be discerned in the literature, based on the standard of instrumentation and procedures used for indoor climatic measurements.

Class III: Field studies based on simple measurements of indoor temperature and possibly humidity at one height of measurement above the floor. Possibly asynchronous and non-contiguous physical (temperature) and subjective (questionnaire) measurements. The majority of field studies used in the derivation of the early adaptive models by Humphreys [100–102] and Auliciems [65] were Class III. While the quality of this data class does not necessarily allow explanatory analyses, if the research questions being asked require only simplified statistical techniques, then this class offers the widest range of published data.

Class II: Field experiments in which all physical environmental variables (t_a, t_r, v, rh, clo, met) necessary for the calculation of heat-balance SET* and PMV/PPD indices were collected at the same time and place as the thermal questionnaires were administered, but most likely only at height of measurement. Humidity measurements taken by aspirated psychrometer or absorption rh sensors. Air speeds measured by hot wire probes with thresholds above 0.1 m/s and/or directional sensing elements and/or time constants exceeding the threshold required for turbulence intensity assessments. By measuring the main physical parameters influencing comfort, Class II data allows an assessment of the impact of behavioral adjustment and control on subjective responses.

Class I: Field experiments in which all sensors and procedures are in 100% compliance with the specifications contained in ASHRAE Standard 55 [7] and ISO 7730 [8]. Three heights of measurement above floor level as specified in ASHRAE and ISO standards (0.1, 0.6 and 1.2 m). All measurements done with laboratory-grade instrumentation, including fast-response omnidirectional anemometry capable of turbulence intensity assessments. The three ASHRAE TC 2.1 sponsored field experiments in the San Francisco Bay Area [32,103], Townsville [104–106] and Montreal [107] are examples of Class I investigations. Data in this class allow more careful examination of the effects of non-uniformities in the environment, as well as of results across different buildings which all have the same high quality data.

4.1. Evidence of adaptation using Class III data

The typical cross-sectional field study of thermal comfort consists of a questionnaire with rating scales administered to

[1] Abdulshukor, Human Thermal Comfort in the Tropical Climate. Unpublished PhD thesis, University of London, London, 1993, (cited by Ref. [23]).

building occupants while simultaneously recording indoor climatic variables, the most important of which is air temperature. Using a thermal sensation or comfort scale, thermal comfort is operationalized as a vote coinciding with the scale's central category ('neutral', or 'comfortable', respectively) [108]. The ambient temperature found by statistical analysis to most frequently coincide with this central rating is referred to as that sample's 'neutrality' and is denoted here as T_n. Numerous such studies have been published over the years and have served as the basis for a series of widely cited adaptive models.

A notable review by Humphreys [100] of 36 examples of Class III studies from various countries around the world uncovered a strong statistical dependence of thermal neutralities (T_n) on the mean levels of air or globe temperature (T_i) recorded *inside* the buildings:

$$T_n = 2.56 + 0.83T_i \quad (r = +0.96) \tag{1}$$

It was noted that building occupants were able to find comfort in indoor temperatures spanning more than 13°C. Humphreys [100] attributed this to the adaptive processes, concluding that "...the range of recent experience is better regarded as one of the factors which will contribute to the acceptability of the environment to which the respondent is exposed".

The next development examined people's adaptation to the *outdoor* climate, based on Auliciems' reasoning that both indoor temperatures and occupants' thermal expectations are dependent, to varying extents, on outdoor temperatures [109]. Humphreys [102] parameterized 'outdoor climate' as simple mean monthly temperature (T_m) and analyzed the data separately for 'climate-controlled buildings' with centralized HVAC and 'free running buildings' which had neither centralized heating nor cooling (i.e., naturally ventilated). The results are depicted in Fig. 1 with the following best fit equations:

(free-running buildings)

$$T_n = 11.9 + 0.534T_m \quad (r = +0.97) \tag{2}$$

(climate-controlled buildings)

$$T_n = 23.9 + 0.295(T_m - 22)\exp(-((T_m - 22)/(24\sqrt{2}))^2) \quad (r = +0.72) \tag{3}$$

The influence of external climate on indoor neutralities is particularly evident in the 'free running' buildings, where the steeper regression model accounted for 94% of the variance in neutralities. In comparison, climate-controlled buildings had a less pronounced but still highly significant correlation with outdoor mean monthly temperature.

Auliciems [65] conducted yet another analysis of the earlier Class III studies by first deleting incompatible field studies from Humphreys' database, such as those based on asymmetric rating scales or children as subjects and then

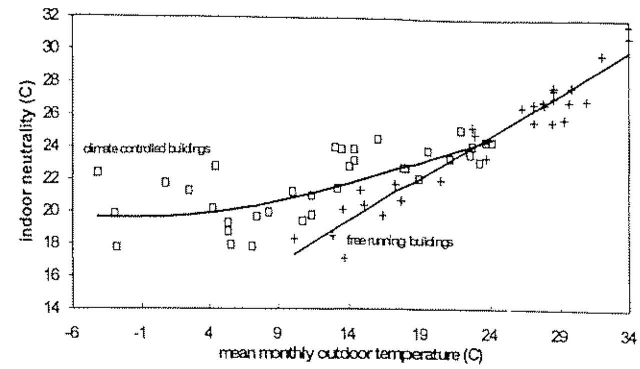

Fig. 1. The statistical dependence of indoor thermal neutralities on climate [101].

adding more recent studies that had been published since the earlier work. These revisions brought the database up to 53 separate Class III field studies from various climatic zones in Australia, Asia, the Americas and Europe. After pooling free-running and climate-controlled building samples together, the resulting linear regression equation was:

(all buildings)

$$T_n = 0.48T_i + 0.14T_m + 9.22 \quad (r = 0.95) \tag{4}$$

Even though the regression coefficients may be unstable in such a model due to intercorrelation between the two independent variables, Eq. (4) represents a widely cited statistical expression for the adaptive hypothesis of human thermal perception.

While the statistical association between neutralities and prevailing outdoor climate appears quite strong and convincing in Fig. 1, the actual *causal mechanism* is still left in doubt by these earlier 'black box' adaptive models. In the warm climate studies (to the right-hand side of Fig. 1), behavioral adjustments such as reduced clothing and metabolic rate and higher air velocities (resulting from adjustments to fans or operable windows), quite possibly shifted thermal neutralities up the temperature scale. But this is only a speculation in the absence of more rigorous data and is also only one type of adaptation. More recent field studies and experiments enable us to begin quantifying the specific causal mechanisms driving thermal adaptation indoors

4.2. *Direct evidence for behavioral adaptation–adjustment*

An early example of a study that examined behavioral adaptation was conducted by Macfarlane [110] on subjects born in the humid tropics of Australia. He showed that, by utilizing behavioral adjustments such as wearing light clothing and restraining physical exertion, local inhabitants were able to reach acceptable comfort in what—to immigrants from cold climates—could be quite uncomfortable, if not stressful, combinations of heat and humidity. Fishman and Pimbert [27] looked closely at weekly clothing patterns of 26 subjects in a UK office building for an entire year. Their estimated clo values had a strong linear dependence on outdoor weather and season, especially in the case of women subjects, with a regression gradient of −0.02 clo units per degree of outdoor mean weekly temperature. This supports the hypothesis that the statistical dependence of indoor neutrality on outdoor climate may be due, in part, to behavioral adjustments that directly affect the heat balance.

The influence of clothing adjustments on neutrality was directly investigated by Humphreys [111] and Nicol et al. [112], as part of a study of office workers in naturally ventilated buildings in North West Pakistan. They found that the office workers were comfortable across a wide range of seasonal temperatures, with neutralities varying between 15.7°C in winter and 26.4°C in summer and concluded that some (half to two-thirds), but not all, of the seasonal changes in comfort temperature could be attributed to the flexibility in the traditional Pakistani clothing worn. While this supports the hypothesis that people use clothing adjustments to adapt to a wide range of temperatures, it also suggests that there may be additional non-behavioral ways in which people adapted to the environment.

Nicol and Raja [113] looked at temporal patterns in behavioral adjustments and found that clothing changes were more strongly dependent on the succession of outdoor temperatures that occurred *prior* to the measurement, compared to the instantaneous or daily mean outdoor temperature, or the instantaneous indoor temperature. Baker and Standeven [13] found a similar pattern, where clothing was not typically used to improve comfort on an hourly basis, but was more strongly based on people's expectations in the morning about what the external thermal conditions might be that day. The Nicol and Raja [113] study also found a significant correlation between temperature and posture as an adaptive behavior. As it got warmer, the posture changes would tend to reduce the effective insulation of the clothing, while increasing the effective body surface area available for sweating.

In addition to adjusting oneself to the environment, one can directly manipulate the environment itself. Baker and Standeven [13,53] used hourly questionnaires to ask whether subjects had made adjustments to their clothing or to furniture, doors, windows, shades, fans or any other part of the building to improve their comfort. Results indicated extensive occupant interaction—for 23 subjects in 7 buildings, over a total of 864 h—there were a total of 273 adjustments to controls or other environmental aspects of the room and 62 adjustments to clothing. Benton and Brager [114] conducted a field study of thermal comfort which addressed the availability, use and effectiveness of both personal and environmental behavioral adaptation. While environmental modification mechanisms such as operable windows, blinds, or heaters were infrequently cited, when they were operated they consistently received high ratings for effectiveness. Personal behavioral mechanisms such as 'take a break', or 'hot or cold drink' received the highest number of citations, even though they yielded slight improvements in thermal comfort. When asking specifically whether the subject had made changes during the last hour prior to filling out the survey, Benton and Brager [114] found that only 12% of the people had adjusted their clothing, although when they did it was given a relatively high effectiveness rating.

4.3. Direct evidence for psychological adaptation–expectation

Psychological adaptation refers to an altered perception of, or response to, the thermal environment, resulting from one's thermal experiences and expectations. The role of personal control has been frequently cited as a key factor influencing this adaptive mechanism. Paciuk [61] provided a direct analysis of the distinction between *available* control (adaptive opportunity), *exercised* control (behavioral adjustment) and *perceived* control (expectation) and found that perceived degree of control was one of the strongest predictors of thermal comfort and had a significant impact on both comfort and satisfaction. This finding was also supported by the work of Williams [115] in her study in office buildings in the Northwest of England, where subjects expressed higher levels of satisfaction when they *perceived* themselves to have more control over their environment. Perception of control can be influenced by a variety of building features, including the envelope, mechanical systems and occupant density patterns. A good example of the latter comes from Leaman and Bordass [116], who administered a standardized questionnaire to thousands of office workers across the UK, including a 7-point bipolar scale asking respondents to rate their perceived degree of environmental control. The results revealed a strong inverse relationship between perceived control and the number of persons sharing the same space.

The role of personal control on expectation and thermal response has important implications in naturally ventilated vs. centrally air-conditioned buildings. The adaptive hypothesis implies that if occupants in a centrally-controlled building have generally experienced fairly constant and uniform conditions, with limited opportunities for personal control, then they not unreasonably expect their building to automatically provide them with perfect comfort. And when it fails to meet those expectations, they will be more likely to judge that building harshly compared to a situation were they had control over those conditions. Evidence of this was presented by Paciuk [60,61], who found that personal or environmental adjustments in air-conditioned buildings actually had a small *negative* effect on satisfaction. Gagge and Nevins [25] and Elder and Tibbott [117] both found very widespread thermal dissatisfaction among the occupants of North American air-conditioned office buildings that were subjected to setpoint adjustments of only a few degrees. In a study conducted by Black and Milroy [118] in both air-conditioned and naturally ventilated office buildings in London, occupants in centralized air-conditioned buildings expressed more complaints about minor temperature fluctuations, even though the naturally ventilated buildings experienced much greater variability. In a year-long study in a mixed-mode UK office building, Fishman and Pimbert [27] found that, as temperatures rose

Table 1
Thermal comfort experiments in the field: observed and predicted neutralities in relation to outdoor climate

Location and season	Reference	Control strategy	Mean outdoor temperature (°C)	Neutral temperature (°C)		PMV residual [a] (°C)
				Observed neutrality	PMV model	
Melbourne-summer	[30]	NV	19.8	21.8	23.9	+2.1
Melbourne-summer	[30]	AC	20.3	22.7	23.5	+0.8
Brisbane-summer	[30]	NV	24.9	25.6	25.0	−0.6
Brisbane-summer	[30]	AC	24.4	23.9	24.1	+0.2
Darwin-dry	[30]	AC	25.2	24.2	23.6	−0.6
Darwin-wet	[30]	AC	28.9	23.9	24.2	+0.3
San Francisco-winter	[32]	AC	12.8	22.1	22.7	+0.6
San Francisco-summer	[32]	AC	18.7	22.6	23.4	+0.8
Townsville-dry	[105]	AC	19.4	24.2	23.0	−1.2
Townsville-wet	[105]	AC	27.0	24.6	23.6	−1.0
Montreal-summer	[107]	AC	18.1	24.0	23.4	−0.6
Montreal-winter	[107]	AC	−6.0	23.1	22.0	−1.1
Hong Kong-summer	[123]	AC	27.7	23.5	23.1	−0.4
Hong Kong-winter	[123]	AC	16.6	21.2	21.7	+0.5
Bangkok	[34]	NV	28.6	28.5	25.1	−3.4
Bangkok	[34]	AC	30.5	24.5	23.7	−0.8
Singapore	[35]	NV	27.1	28.5	25.7	−2.8
Singapore	[35]	AC	27.4	24.2	24.4	+0.2

[a] Residual = predicted − observed.

above 24°C, people in centrally air-conditioned work areas began voting much higher on the thermal sensation scale than their colleagues in the naturally ventilated work areas, suggesting that they were less tolerant of higher temperatures and expected a higher standard in the thermal environment. Rowe et al. [40] looked at studies in air conditioned buildings and naturally ventilated buildings both with and without supplementary on-demand cooling and heating equipment. He found a significantly higher level of satisfaction in the naturally ventilated buildings with additional supplementary control and concluded that people have a wider tolerance of variations in indoor thermal conditions if they can exert some control over them.

Similar patterns can be found in thermal comfort field studies of homes vs. office buildings, where a multitude of contextual factors, including perceived control, might influence expectation and thermal response. Hunt and Gidman [119] found an unusually low average household temperature of 15.8°C in a national survey in the UK and suggested that residences were motivated to use adaptive mechanisms to stay comfortable at these lower temperatures in order to reduce their heating bills. Cena et al. [120] studied the thermal comfort of healthy, independently living elderly subjects in their own homes. Neutralities were much lower than predicted by PMV and analysis suggested that the subjects psychologically adjusted to the cool thermal environment in their homes. Oseland [38,39] conducted a large number of field studies in UK homes and offices using a variety of methods and consistently found that thermal neutralities and preferences were significantly lower in the home compared to the offices and the differences could not be accounted for by changes in clothing, activity, or air velocity. Similar findings were reported by Pimbert and Fishman [121], where preferred temperatures in UK homes were up to 2°C cooler than those in offices. All of these patterns support the notion that people grow to accept the thermal conditions to which they become accustomed to [122] and that this acceptance might be influenced by factors such as personal control, energy bills, or concern for the environment and the associated societal pressures to conserve energy [120].

4.4. Analyzing neutral temperatures with Class I and Class II data

As noted earlier, Humphreys' and Auliciems' analyses of Class III field studies had the advantage of looking at cumulative data from multiple field studies conducted in a range of climates, but were limited in their ability to determine the *causal* mechanisms behind the apparent adaptation. And while the field studies described in Sections 4.2 and 4.3 were able to look at specific mechanisms, such as behavioral adjustments or perceived control, each study was conducted in a limited climate and building context. The next step in evaluating field evidence for thermal adaptation uses results from a range of Class I and Class II field studies that have measured all the environmental and personal variables necessary as inputs to the traditional heat balance models. By comparing observed and predicted thermal responses, one can then distinguish between the influences of behavioral adaptive mechanisms that are accounted for in the heat balance models (i.e., clothing, air movement, etc.) and psychological adaptive mechanisms which are not.

Table 1 summarizes the results from 18 Class I and Class II field studies (listed in chronological order), conducted by seven research teams in a range of climates and seasons and in both air-conditioned and naturally ventilated buildings [30,32,34,35,105,107,123]. These particular field studies were selected because of their consistent methods, including instrumentation, questionnaire, protocols and analysis. This permits climatic and contextual effects to be disentangled from the dozens of methodological artifacts that potentially confound earlier investigations. Neutral temperatures are listed as observed and predicted using the PMV model [18]. The differences between predicted and observed neutralities are also listed, with positive numbers indicating that neutralities were over-predicted by the PMV model. It should be noted that the PMV predictions may differ from those presented in the original publications, because all calculations reported here increased the average clo values by 0.15 clo units, to account for the insulation value of a typical office chair [47]. In most cases, this had the net effect of lowering the PMV model's predicted neutrality by over a full degree.

While the original publications can be referred to for the details of each study, an immediate observation here is that, with the exception of Brisbane, the largest discrepancies between PMV-predicted and observed neutralities occur in the naturally ventilated buildings. The poor predictive capabilities of PMV in these buildings implies that adaptive processes other than behavioral adjustment (which are accounted for in the heat balance models) must be occurring and expectation seems the most likely explanation since acclimatization has all but been eliminated by laboratory experiments. The naturally ventilated buildings probably had occupants who perceived a higher degree of personal environmental control by comparison to their counterparts in centrally air-conditioned office buildings. Within the adaptive hypothesis, such buildings would be expected by their occupants to provide variable indoor temperatures and therefore be judged less critically than centrally air-conditioned buildings.

5. Discussion

5.1. Thermal comfort predictive models

It is our view that the adaptive and heat balance approaches to modeling thermal comfort are complementary, rather than contradictory. At some level, the static heat balance model can be considered as *partially* adaptive in the behavioral sense, since it accounts for clothing and indoor climatic parameters which can be adjusted by the occupant. As a result, the heat balance model does, in fact, predict comfort temperatures moving in the direction of prevailing outdoor climate—as seen in the offset of winter and summer comfort zones that result from differences in seasonal clothing patterns [7]. The limitation here is that the input variable of clothing level is the *only* underlying basis or cause for the shift in temperature. The heat balance model does not account for the feedback that might initiate this or other behavioral responses, nor does it account for the contextually related expectations. On the other hand, while the earlier adaptive models describe an empirical relationship between neutral temperatures and exposures to both the indoor and outdoor climates, they are unable to articulate the underlying causal relationships. We believe that only through a combination of the features of both these modeling approaches will we eventually be able to account for both the thermal and non-thermal influences on occupant response in real buildings.

Given that heat balance models account, to some extent, for the effects of behavioral adjustments, the challenge in this area is twofold. First, when using the model to assess *existing* thermal comfort conditions, it is critical that field methods accurately measure thermal conditions directly at the occupant's location in space and time and that careful assessments are made of activity and clothing levels, including the effect of the chair. Secondly, when the model is used to *predict* thermal conditions resulting from design decisions, one needs to carefully estimate what the anticipated clothing and activity levels will be and how people's use of local environmental controls will affect the indoor thermal environment. It is this latter point that is possibly the more formidable and the area where an adaptive model could make an important contribution by taking account of the feedback loop between discomfort and purposive behavioral thermoregulation. This would eliminate the need, in some cases, to guess what the clothing patterns of future, unknown occupants might be.

5.2. Natural ventilation vs. air-conditioning

Our review of field evidence for thermal adaptation shows a clear distinction between the responses of occupants in naturally ventilated buildings as opposed to air-conditioned buildings. The data also showed that this difference could not be entirely accounted for by adjustments to clothing or activity. The most plausible explanation for these differences is the contextual influence of thermal history and its effects on expectations—past thermal experiences in a building create a benchmark for expectations of future thermal performance. In naturally ventilated buildings, indoor temperatures more closely match the diurnal and seasonal variations in outdoor temperatures. People recognize this, relax their expectations or individual 'comfort criteria' and not only become more tolerant of the more varied, dynamic and non-uniform indoor conditions, but often prefer having a closer connection with weather and seasonal changes. Comfort ultimately depends on the degree to which the environment matches and contributes to our expectations and studies have consistently shown that this is strongly affected by our sense of whether or not conditions are under our control [61,124–127].

Expectation plays a role for occupants of air-conditioned buildings as well, but in a different way. Here, thermal history comprises consistently cool, constant, uniform conditions, creating more stringent comfort criteria while biasing expectations towards constant HVAC setpoints rather than daily or seasonal fluctuations. Air-conditioned occupants were basing their evaluations on the benchmark of their own preconceptions of what air-conditioning should achieve (an expectation of constancy), rather than on what it actually provided. In effect, this suggests that increasing levels of sophistication in environmental control systems and building services are on a treadmill of attempting to satisfy increasingly stringent occupant expectations [124].

5.3. Building controls

The advantages of developing environmental control algorithms based on an adaptive comfort model include: (1) ability to be implemented into either new or existing buildings as a relatively low-cost retrofit strategy; (2) potential energy savings by allowing setpoint temperatures to track the outdoor weather and climate, particularly in the less extreme Spring and Autumn seasons; (3) comfort improvements, by relating more directly to context-dependent and variable preferences of the occupants; and (4) a more integral approach to designing buildings that can operate along a continuum between passive and active modes of operation [128]. Ideally, adaptive building controls would strike a balance between fully automated controls at the system side and manual controls that the users are able to alter [129].

Current control strategies typically adopt a building-centered, energy-consuming approach that focuses on creating constant, uniform neutrality-conditions which might actually be perceived by some as thermal monotony or sensory deprivation [130]. In contrast, a person-centered approach would purposely provide, or at least permit, variability across time and space. Spatially, we might design for thermally differentiated areas to allow for individual thermal requirements [130,131]. Temporally, we might permit a gradual drift of indoor temperatures towards outdoor conditions in a way that would enable and encourage adaptations such as clothing changes and use of operable windows [132,133].

Auliciems [132] was the first to propose such an adaptive algorithm, premised on the adaptive model described in Eq. (4), and suggested that the averaging period for the algorithm's temperature inputs should be a running mean based on hourly observations across the preceding fortnight. More recently, Humphreys and Nicol [133] proposed a similar adaptive algorithm for UK office temperatures, in which an outdoor temperature index is defined by combining *current* outdoor temperature with an exponentially-weighted running mean of the *preceding* week's daily mean outdoor temperature in a ratio of 3:7. This outdoor temperature index (T_{oi}) is then used to specify the target indoor temperature (T_i) using the following relation:

$$T_i = 0.534 T_{oi} + 12.9 \quad (5)$$

Nicol and Roaf [134] also proposed an adaptive algorithm, suitable for Pakistan, using a simple outdoor temperature calculated from the preceding month (T_m):

$$T_i = 0.38 T_m + 17.0 \quad (6)$$

One concern regarding both Eqs. (5) and (6) might be that they represent an air-conditioning application of regression equations derived from naturally ventilated buildings. Their suitability for a control algorithm is therefore uncertain, given the different levels of adaptive opportunity and thermal expectations among occupants in these two quite distinct architectural contexts.

5.4. Thermal comfort standards

As mounting evidence confirms that thermal perceptions are affected by recent thermal experiences, it seems increasingly unreasonable to expect that a universal standard can be applicable for all people, all buildings and all climate zones [21]. Current comfort standards tend to discourage or preclude the design of naturally ventilated buildings because, without accounting for the effects of expectation and higher levels of perceived control on thermal satisfaction, they predict that the more variable conditions found in naturally ventilated buildings will be uncomfortable. They are also limited in their usefulness to building designers who want to use thermal qualities to help shape their design decisions. Being based solely on a goal of 'neutrality', regardless of context or the nature of the design problem, these standards disregard the more dynamic, experiential qualities of the indoor environment that may also be appropriate design goals [135].

An adaptive model is needed to modify existing standards to more appropriately account for contextual effects. A variable temperature standard would link indoor temperatures to the climatic context of the building, thereby accounting for past thermal experiences and thermal expectations of their occupants. ASHRAE has recently funded work in this area in which new analysis of existing data collected from Class I and Class II field experiments worldwide produced a proposal for a variable temperature standard. A unique feature of this work is that the proposed standard takes two different forms for centrally-controlled air-conditioned buildings vs. naturally ventilated buildings [99].

6. Conclusions

The adaptive approach to modeling thermal comfort acknowledges that thermal perception in 'real world' settings is influenced by the complexities of past thermal history, non-thermal factors and thermal expectations. Thermal adaptation in the built environment can be attributed to three different processes—behavioral adjustment, physiological acclimatization and psychological habituation or expectation. Evidence reviewed in this paper indicates that the slower physiological process of acclimatization appears not to be so relevant to thermal adaptation in the relatively moderate conditions found in buildings, whereas behavioral adjustment and expectation have a much greater influence and should therefore be the focus of future research and development in this area.

One of the most important findings from our review of field evidence was the distinction between thermal comfort responses in air-conditioned vs. naturally ventilated buildings. Analysis suggested that behavioral adaptation incorporated in conventional heat balance models could only partially explain these differences and that comfort was significantly influenced by people's expectations of the thermal environment. Occupants in naturally ventilated buildings had more relaxed expectations and were more tolerant of temperature swings, while also preferring temperatures that tracked the outdoor climatic trends. In contrast, occupants in closely controlled air-conditioned buildings had much more rigid expectations for a cool, uniform, thermal environment and were more sensitive to conditions that deviated from these constant setpoints. These contextual differences most likely resulted from a combination of past thermal history in the buildings and differences in levels of perceived control. It is, therefore, essential that adaptive algorithms for comfort control utilize regressions from the architectural context for which they are intended. Regressions based on data from naturally ventilated buildings will probably be unsuitable as a control algorithm for air conditioned buildings in which adaptive opportunities are severely constrained.

There are numerous benefits to be gained from an improved understanding of the influence of adaptation on thermal comfort in the built environment. These potentially include improved predictive models and standards, more sophisticated and responsive environmental control algorithms, enhanced levels of thermal comfort and acceptability among occupants, reduced energy consumption and the encouragement of climatically responsive building design. These benefits can best be achieved through an ongoing, open dialogue and collaboration between the proponents of the 'adaptive' vs. 'heat balance' approaches and we hope that our paper has provided a foundation for that to occur.

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