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Perspective

A Day Designed Against the Heat: A Human Biometeorological Perspective on Daily Adaptation

Andreas Matzarakis [1,2]

[1] Environmental Meteorology, Institute of Earth and Environmental Sciences, University of Freiburg, 79085 Freiburg, Germany; andreas.matzarakis@meteo.uni-freiburg.de
[2] Democritus University of Thrace, GR-69100 Komotini, Greece

Abstract

Heat is now one of the leading weather-related causes of death worldwide, and unlike a flood or a storm, its damage rarely arrives in a single moment. It accumulates, mostly indoors and mostly at night, through physiological stress that builds across hours rather than striking all at once. This perspective proposes a human biometeorological framework that reads heat adaptation through the sequence of a single hot day, from the cool morning to nocturnal recovery, rather than through a list of technologies. Physiologically Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI), both developed for the outdoor thermal environment, translate atmospheric conditions into a load the body carries. They give households, workplaces, care facilities and cities a common language for timing, shading and ventilation. Indoors and at work, the established indices and standards for the indoor thermal environment and for occupational heat stress remain the tools of choice, and the framework is meant to complement them. Particular weight is given to overheating indoors, to the people for whom recovery is hardest to reach, and to the unequal distribution of tropical nights. The central argument is that successful adaptation depends less on any single measure than on managing the cumulative heat load across the whole day. A climate-resilient city, on this view, is one that supports physiological recovery through its buildings, its neighbourhoods and the daily choices its residents are able to make.

Keywords: heat adaptation; human biometeorology; physiologically equivalent temperature; thermal comfort; indoor thermal environment; building overheating; tropical nights; urban heat island; heat–health action plans; shade

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1. Introduction

Heat is now one of the leading weather-related causes of death worldwide. Unlike a flood or a storm, its damage rarely arrives in a single moment: it accumulates, mostly indoors and mostly at night, through physiological stress that builds across hours rather than striking all at once [1]. What a body carries by the end of such a day depends less on the outdoor peak than on when the heat arrived, how the building responded to it, what choices were made along the way, and whether the night gave it room to recover.

Hippocrates opens *Airs, Waters, Places* by telling the physician to study the winds, the waters and the seasons of a town before treating anyone living in it [2]. Human biometeorology puts this instinct into numbers: indices such as the Physiologically Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI) describe the exchange of heat between a body and its surroundings, not the air alone [3–5]; in Germany the method

is laid down in guideline VDI 3787 Part 2 [6]. What has been missing is the translation of that number into the ordinary course of a day, in a language a household, a care facility, a workplace or a municipal administration can act on. This perspective attempts exactly that translation, by following a single hot day from before sunrise to the following night.

A word on scope. PET and UTCI were developed to describe the outdoor thermal environment, and that is where they are used here. Indoors and at the workplace, separate standards exist for building overheating and for heat stress at work (for example ISO 7730, EN 16798-1, ISO 17772-1, ISO 7933, ISO 7243 and ISO 15265) [7–14]. Among these, the WBGT is an empirical index, whereas PMV and the Predicted Heat Strain model are built on the heat balance of the human body [8,15]. These methods answer questions that an outdoor biometeorological index was not built to answer, for example how long a person may work under given conditions. Overviews of the many thermal indices, their basis and their fields of application are given in [16–18]. This perspective therefore uses PET and UTCI for the outdoor setting and as a common language, and it points to the indoor and occupational methods wherever the setting is a room or a workplace. The Freiburg examples are illustrations: the timing of the phases of a day, and the values that go with them, depend on climate, season and latitude.

2. A Human Biometeorological Day

2.1. Human Biometeorology and the Scale of the Problem

Human biometeorology has the tools to describe a hot day in terms that matter to the body. PET and UTCI combine air temperature, radiation, wind, humidity, activity and clothing into a single physiologically meaningful number, and the difference from air temperature alone is not academic: at the same air temperature, radiation and wind can move the actual heat load by many degrees [3–5].

Both indices are expressed in degrees Celsius and are read against their own stress scales. The table and figure below therefore give PET and UTCI side by side, so that the reader can see how close the two run to each other and where they differ.

The scale of the problem is well-documented. The summers of 2003 and 2022 are associated with tens of thousands of additional deaths in Europe [19,20], and a pan-European analysis puts heat-related deaths in the summer of 2024 alone at around 62,700, on top of more than 61,000 in 2022 [21]. Provisional figures for 2026 point in the same direction: the Robert Koch Institute estimates about 16,000 heat-related deaths in Germany for calendar weeks 15 to 37 of 2026, about half of them in people aged 85 and older [22]. Heat stress measured with the UTCI has increased in many regions since the 1970s, extreme heat stress now occurs about two and a half times as often in Europe, and a growing share of the world population is exposed to hazardous heat [23]. Indices built on the human heat balance have long been used for outdoor assessment, and epidemiological studies that compare them with air temperature give a mixed picture: in some studies the indices perform better; in many they do not [24,25]. The indices describe how severe the environment is for the body; they do not replace health data.

The question that matters for adaptation is not whether a day is hot, but when, where and for whom it becomes dangerous. That is the question the rest of this perspective is built around, treating the day itself as the working unit of adaptation.

2.2. The Rhythm of the Day: Using the Cool Morning and Avoiding the Peak

The early morning is the most useful part of a hot day, and it is free. Outdoor work, errands and physical activity belong here, before the sun gains strength, because physical effort adds its own heat to whatever the atmosphere is already contributing [26]. The same hours are the moment to ventilate, while outdoor air still runs cooler than indoor air, and

then to close the building down again as radiation increases: shutters closed, windows shaded, before the room has had the chance to warm.

Through the middle of the day, adaptation is less about doing and more about not doing. Shade, or a cooler room; fluid before thirst arrives; the lightest possible physical load; rest where rest is possible. In the evening, ventilation can resume once the air outside is genuinely cooler than the air inside, though humidity, air quality, safety and insects will all have their say in exactly when.

None of this is new. Shaded courtyards, heavy walls, controlled ventilation, an afternoon rest and water used for cooling have been used in hot climates for as long as people have built houses in them. The wind towers and underground water channels of Iranian desert towns are one well-documented example [27]; the courtyard houses of the Mediterranean, with their thick walls, shuttered windows and the afternoon rest, are another, and Xenophon already let Socrates recommend a house that takes the low winter sun and stays in the shade in summer [28]. The street is a separate matter. Measurements in a Freiburg street canyon show why the geometry of a street matters as much as the technique used within it: canyon shading changes the radiant load on a pedestrian far more than it changes the air temperature [29]. Adaptive thermal-comfort research makes the same point from a different angle: people tolerate a wider range of conditions once they can adjust their clothing, their activity and their immediate surroundings [30]. The aim is not to reproduce one traditional practice everywhere, but to recognise the physiological logic behind all of them.

Passive measures such as night ventilation, thermal mass and external sun protection reduce overheating in buildings [31]. Across Europe, people have so far tolerated rising temperatures better than projections without adaptation assume, and better housing and wider access to air conditioning are the likely reasons [32]. The cool morning is a practical opportunity, and one of the cheapest available. Table 1 and Figure 1 summarise these phases and the actions recommended for each, using the hottest day of the June 2026 heat wave at the Freiburg roof station as an illustration. The times and the values belong to this place and this day. In another climate, in another season or at another latitude the phases shift, and the PET values with them. The value of 23 °C is used as a reference value for the border between comfortable and slightly warm conditions, not as a threshold for health.

Table 1. Phases of a hot day, thermal context and recommended actions. PET and UTCI ranges (°C; in the sun and in the shade) were calculated from hourly measurements at the roof station of the University of Freiburg on 27 June 2026 (night: 27–28 June). They are illustrative of one hot day in one place and are not universal thresholds. PET stress classes follow [4,33].

Phase	Time	Indicative Thermal Context (PET, UTCI in °C)	Primary Adaptation
Morning window	05–09	Coolest part of the day, in this heat wave still above the 23 °C reference value. PET 24–37 (sun), 24–33 (shade); UTCI 25–33 (sun), 25–31 (shade)	Outdoor activity; ventilation; pre-cooling
Rising heat	09–12	Strong increase of thermal stress in the sun. PET 37–44 (sun), 33–38 (shade); UTCI 33–39 (sun), 31–36 (shade)	Complete essential outdoor tasks; initiate shading
Peak heat	12–17	Extreme heat stress in the sun, strong stress also in the shade. PET 44–50 (sun), 38–42 (shade); UTCI 39–44 (sun), 36–39 (shade)	Reduce exposure; use shade or cooler rooms; hydrate; targeted cooling
Late afternoon	17–20	Heat remains very high. PET 40–49 (sun), 37–42 (shade); UTCI 38–43 (sun), 37–39 (shade)	Gradual return to outdoor activity; check indoor conditions
Evening	20–23	Relief once the sun is low, air still hot. PET 29–40 (sun), 29–38 (shade); UTCI 29–38 (sun), 29–37 (shade)	Cross-ventilate when outdoor air is cooler; prepare bedrooms
Night	23–05	Warm night, no relief for the body. Air 30–33 °C; PET 25–29; UTCI 26–29	Protect sleep; ventilate when effective; monitor vulnerable people

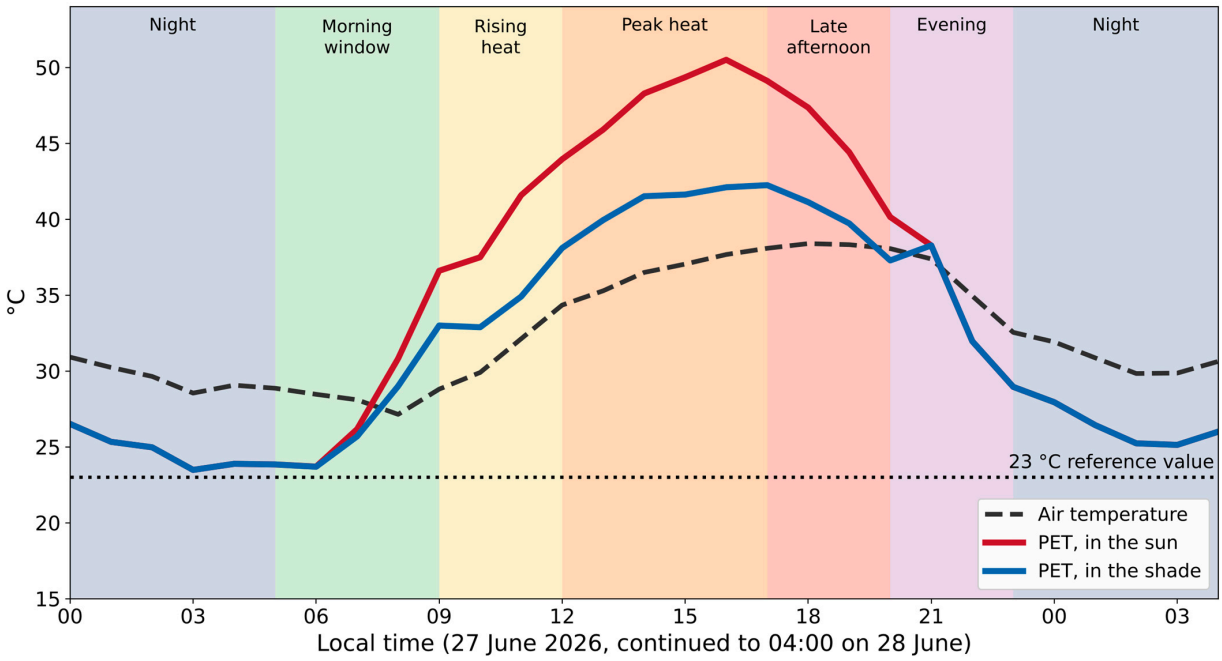


Figure 1. Observed course of air temperature and PET in the sun and in the shade at the roof station of the University of Freiburg on 27 June 2026, the hottest day of the June heat wave, with the phases of the day used in Table 1. PET was calculated from hourly measurements (air temperature, humidity, wind, global radiation) for a standard person; the dotted line marks the 23 °C reference value. The phases illustrate this day and place.

2.3. Air Conditioning: A Targeted Refuge, Not a 24-Hour Strategy

Mechanical cooling changes the thermal conditions of peak heat substantially, but it works best alongside passive and behavioural measures, not as their replacement. The practical sequence is simple: ventilate while conditions allow, shade the windows that catch the sun, cut unnecessary internal heat gains, and only then bring in mechanical cooling for what remains.

The right set point is a matter of comfort, health, energy use and the gap between indoor and outdoor temperature, not a fixed rule, and a large temperature contrast is not itself a sign of good protection. Simulation studies of night-time ventilation show the timing point: the cooling depends on the air flow during the night, on thermal mass and on internal heat gains, and natural ventilation works least well in the warm periods when it is needed most [31]. These recommendations are context-specific. The right sequence depends on climate, building, occupants and electricity supply, and not every household can follow it.

Access to mechanical cooling is also unequal. The households most exposed, in dense neighbourhoods and older housing, are often the ones least able to buy or run an air conditioner. That is a health-equity problem in its own right, and a planning one too, since cooling switched on everywhere at once strains the electricity grid precisely when it is most needed. Passive measures stay important even where mechanical cooling is available, not instead of it.

2.4. Indoors: Where the Heat Load Is Really Decided

For most people, most of a hot day happens indoors, and indoor conditions deserve the same attention as the street outside, not less, because heat stored in a building can outlast the afternoon that put it there [34]. A warning system built only on outdoor conditions misses a large part of what people actually experience.

Measurements from ten monitored workplaces in Freiburg during the hot summer of 2022 make the point directly. Indoor and outdoor exposure differed, and rooms with poor shading sat at moderate to strong heat stress for hours at a stretch [35]. Outdoor temperature alone would not have predicted this. The indoor situation is a different one from the outdoor situation for which PET and UTCI were designed, and the study used them as an exploratory step to describe indoor and outdoor exposure in one unit. For building overheating, tools developed for the indoor environment, such as operative temperature, adaptive comfort models and the overheating criteria of EN 16798-1 and ISO 17772-1, are the appropriate basis [7,8,10,11,34]. For workplaces with heat exposure, the occupational methods named in the Introduction apply.

Four things decide how much heat a building accumulates: how it faces the sun, what it is built from, which floor a room sits on, and how it is cooled. External shading, a well-designed roof and façade, insulation, and night ventilation can all keep heat out without running a machine continuously [36], and the same measures make a building more resilient the day the power goes out.

Indoor monitoring should be as routine as outdoor forecasting. A simple temperature and humidity reading already tells a household something useful, though a full assessment also needs operative temperature, air movement, activity and clothing to say anything precise [7,8]. Figure 2 illustrates this outdoor–indoor contrast with a simple building response model driven by the observed outdoor data.

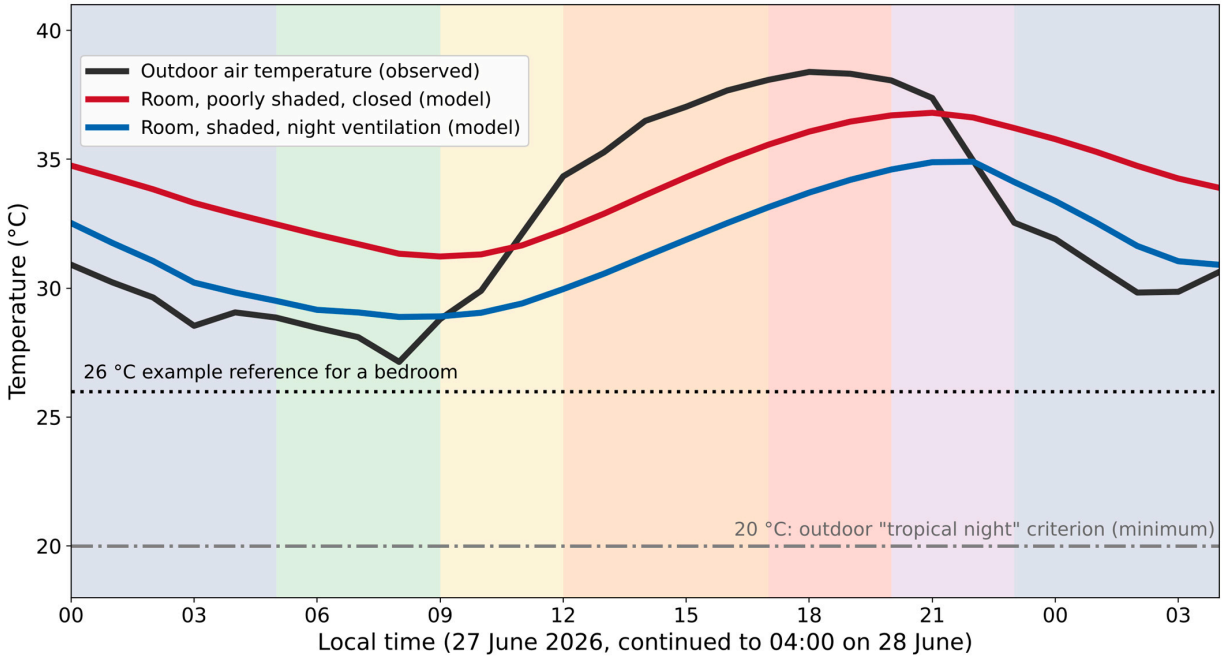


Figure 2. Outdoor air temperature (observed, roof station of the University of Freiburg, 27–28 June 2026) and indoor temperature of two illustrative rooms, calculated with a first-order building response model driven by the observed air temperature and global. The curves are a conceptual illustration of delayed indoor heat and lost night recovery, not measurements. The parameters were chosen for illustration and are not based on a specific building. Dotted line: example reference value for a bedroom; dash-dotted line: minimum-temperature criterion of the outdoor tropical night.

2.5. The Night: The Hours That Decide Recovery

The night is where recovery happens, or does not. Physiological recovery depends on the body's ability to cool, and a warm night can carry the day's strain straight through to the next morning, so heat does not simply reset at sunrise.

A tropical night is usually defined as a minimum air temperature at or above 20 °C. This is an outdoor criterion, measured at a weather station, and it says little about the room in which a person sleeps. A bedroom under a roof can stay far above the outdoor minimum, and a well-ventilated one can follow the outdoor air closely, as Figure 2 shows. In the June 2026 heat wave, the minimum air temperature at the roof station stayed above 26 °C from 26 to 28 June, far above the 20 °C of the criterion. Night-time overheating of dwellings has to be judged with indoor measurements and indoor criteria [10,34], and warm nights are linked to higher mortality in their own right [37]. In a city, stored heat in walls and pavement delays that cooling, and high humidity blunts what evaporative cooling remains available [38,39]. What a warm night actually costs a person depends on this whole combination, not on the minimum temperature alone.

Duration matters as much as any single peak. A run of hot days and warm nights erodes sleep and narrows the margin for recovery night after night, and vulnerability tends to build as a heat episode goes on rather than staying constant [40–45]. The night-time thresholds used in heat–health action plans vary widely between systems, and there is little evidence that they represent the same level of risk everywhere they are applied [46].

Heat–health action plans need to treat the night as a subject in its own right: protecting sleep, providing a cooler room or a public cooling space, and finding the people who have no way to cool their own home.

2.6. Vulnerability: The Same Day Is Not the Same for Everyone

The same day is not the same day for everyone. Age, health, occupation, housing and the freedom to change what you are doing all decide how much a given afternoon actually costs a body.

1. Older adults, especially those living alone, often have a smaller margin: sweating and thirst respond later, medication can interfere with either, and there may be nobody nearby to notice when things go wrong [47–49];
2. Infants and small children cannot regulate their own temperature well and cannot ask for help; they depend entirely on an adult noticing;
3. People with heart or lung disease carry an extra physiological cost during heat, one that can interact with their medication in ways that are easy to miss;
4. Outdoor workers add their own metabolic heat to whatever the weather is already delivering, often with little control over when the work happens;
5. People who are socially isolated, in homes that do not cool well, are the ones most likely to be found too late, simply because nobody was checking.

These are not edge cases. Together they make up a large share of the population a heat–health action plan is actually meant to protect, and a plan built around a healthy adult who can rearrange their schedule, control their indoor thermal environment and afford to run an air conditioner will underestimate exactly the people it should be designed for [50,51].

The figures for 2026 show it. Of the roughly 16,000 heat-related deaths estimated by the Robert Koch Institute for Germany, about 8200 occurred in people aged 85 and older and about 1500 in people under 65 [22].

Housing decides as much as the person. A top-floor flat under an uninsulated roof, a single-aspect room without cross-ventilation, a home without external shading or a cool room, and a neighbourhood without trees, shade or a public cooling space put the same person at very different risk. In the 2003 heat wave in France, living on the top floor and poor thermal insulation were among the factors that raised the risk of death for elderly people living at home [52], and guidance on healthy housing makes the same link between dwelling, thermal conditions and health [53]. Housing quality, access to cooling and the

conditions of the neighbourhood therefore belong next to age, health and occupation when vulnerability is assessed.

The indices have limits of their own. The standard PET and UTCI values and their stress classes refer to a reference person, a 35-year-old man, and the classes were derived for Western and Central Europe [4]. The models accept individual data, but these mainly adjust metabolic rate and body size. They do not describe age-related changes such as reduced sweating and lower skin blood flow [54], nor the effect of medication or chronic disease. Older people may therefore be under more strain than the index value suggests. A lower alert level for them is a sensible, if approximate, way to handle this, and a thermophysiological model that includes these changes is the better answer [55]. The stress classes also shift with climate and adaptation: in Taiwan, the PET ranges at which people felt neutral, warm or hot lay clearly above those found in Europe [33,56]. In another climate the classes should therefore be checked locally, with a survey of the population or with local health data, before they are used for warnings.

Thresholds used in occupational and public-health guidance need to be read with this in mind. A single number rarely carries the same risk for every population it is applied to [50]. For workplaces, the occupational standards and the Predicted Heat Strain model remain the basis, because they include metabolic rate (ISO 8996) [57], work intensity, clothing insulation and evaporative resistance (ISO 9920) [58] and exposure time [8,15]. What human biometeorology can add is a population-specific assessment, treated as a starting point for judgement rather than a clinical cut-off. Table 2 summarises practical protective measures for each of these groups.

Table 2. Vulnerable population groups and practical heat–health measures. Thresholds are not universal clinical limits and should be adapted to the population, climate, exposure setting, and relevant guidance. The indicators in the third column are examples of environmental information; they are not substitutes for occupational heat stress methods (for example ISO 7933 and ISO 7243 [12,13]) or for clinical assessment. Sources: Older adults [47–49]; young children [47,48]; outdoor workers [26,51]; chronic illness [48,49]; socially isolated people [48,52].

Population Group	Main Heat-Related Concern	Context-Specific Indicator	Practical Protection
Older adults	Reduced thermoregulation; reduced thirst; medication effects	PET/UTCI plus warm-night conditions	Welfare checks; cool spaces; hydration support
Young children	Limited thermoregulation and self-care	Age-appropriate heat guidance	Avoid peak exposure; shade; fluids; supervision
Outdoor workers	Exertion plus environmental heat	Workplace standards (e.g., PHS) and workload assessment; UTCI for outdoor communication	Work–rest cycles; morning scheduling; shade and water
Chronic illness	Additional cardiovascular/respiratory load	Population-specific heat guidance	Access to cool environments; clinical advice where appropriate
Socially isolated people	Delayed detection; limited support	Heat warnings plus social vulnerability	Outreach; welfare checks; access to cooling facilities

2.7. When the Machine Fails: What Remains Without Power

Heat adaptation also has to survive the day the power fails. The blackout across the Iberian Peninsula on 28 April 2025 [59] was a reminder of how completely modern life leans on electricity, for cooling, for communication, for healthcare, for nearly everything that keeps a hot day manageable.

When mechanical cooling goes out at the worst possible moment, what is left is whatever was built passively into the place beforehand: shade, cross-ventilation, thermal mass, reflective surfaces, a tree outside the window. None of it needs power.

This is the case for passive survivability. A building that stays reasonably liveable without electricity is more resilient in a heat wave than one whose safety depends entirely on a compressor that may or may not still be running. It is also the strongest argument for building this into design and retrofit now, rather than after the next outage makes the case for us.

2.8. From the Day to the City: Shade, Warning and Neighbourhood

A single day becomes a city's problem once enough people are exposed to it at the same time. A heat–health warning gives the first signal, but acting on it needs more than the warning itself: timing, indoor conditions, the night ahead, and where the nearest cool space actually is [60–62].

Shade does more of the work than most people expect, because human thermal stress answers to radiation more than to air temperature [63,64]. Removing a single tree measurably increases the hours of heat stress across a year, and a tree's shade can cut the mean radiant temperature far more than it cuts the air temperature nearby [65,66].

Urban heat adaptation works best as a combination: shade and ventilation together with building form, surface choice and where the footpaths actually run. Trees, reflective surfaces, buildings oriented to let the wind through, all of these reduce thermal stress while making the street a better place to be regardless of the weather [66,67].

The social side of this matters just as much as the physical side. A neighbour who checks on someone living alone gives a protection that no index or building technology provides. Recent field and modelling work supports this for trees and shade: placement, not just quantity, decides how much good they do where people actually walk [68,69].

3. Discussion

This perspective does not propose a new thermal index or another warning threshold. It proposes the day itself as the unit of analysis, as the frame that links outdoor conditions, the indoor thermal environment, behaviour and physiological recovery together. For adaptation, the heat wave is too coarse a unit; the sequence of exposure and recovery across a single day is more useful.

Warning systems built on outdoor conditions and actual human exposure do not match well. People move between the street, the workplace, home and a care facility, and each of these has its own thermal environment. Heat stored indoors can outlast the afternoon that caused it, and a warm night can remove the one recovery period that would otherwise separate one hot day from the next [35].

For heat–health action plans, this has a direct consequence. A plan that ends at a warning threshold treats a hot day as a single number. Effective adaptation is a sequence of decisions: when to ventilate, when to shade, when to slow down, when to switch on cooling, who to check on, and how to protect the night [61]. Building codes and retrofit programmes should be judged not only by the daytime peak they are designed against, but by whether a dwelling can actually cool down after dark.

The limits of this approach should be stated. It is a conceptual argument built on published measurements and reviews, not a new empirical study, and the right timing for any of these actions depends on climate, construction, air quality, humidity, culture, occupation and individual health. The Freiburg day is one example: in hotter, more humid or colder climates the phases, the PET classes and the best actions differ, and the framework has to be filled in locally. PET and UTCI are useful, but neither is a clinical threshold. No thermal index describes a health outcome by itself. PET and UTCI describe how severe an environment is for the body. Physiological strain, such as core temperature and dehydration over a work shift, is the field of models such as the Predicted Heat Strain model [15,55], and clinical outcomes need clinical judgement. Three levels should therefore be kept apart: the environment (indices such as PET, UTCI or operative temperature), the strain on the body (physiological models) and the health outcome (clinical and epidemiological evidence). The day framework works on the first level and helps people to decide what to do, as an addition to heat–health guidance. It does not replace the methods and standards for indoor spaces and workplaces, and it organises existing evidence rather than replacing guidance built for a specific population.

Its value is practical: it gives a weather forecast a route into building operation, work scheduling, household habit, neighbourhood design and the simple act of looking in on someone. It also keeps recovery visible, which a single daytime number cannot do. Avoiding the midday peak means little if the bedroom is still warm at midnight.

4. Conclusions

Heat adaptation is better understood as managing a cumulative load across an entire day than as a response to a single extreme. The measures that work best combine passive building design, the timing of daily activity, cooling at night, and support from neighbours, not any one of these alone.

Human biometeorology gives this a scientific basis: a way of holding atmospheric conditions, the building, behaviour and recovery together, and connecting outdoor thermal indices, together with the established indoor and occupational standards, to the decisions made by a household, a workplace, a care facility or a city.

Adaptation succeeds when the people most at risk keep the chance to recover every night, whatever their age, health, housing or circumstances. A climate-resilient city therefore takes the human body as its measure: how people live in its buildings and streets, and how they recover in them, day after day. This is also why we are not powerless in the face of heat [70]: adaptation means ordinary days that are planned well.

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