

Where air-conditioning is essential - weather station analysis of limits for passive cooling

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Abstract

This study examines conditions where passive cooling strategies may fail during heat waves and where access to active cooling could be critical for health and resilience. Using reanalysis of 16,582 globally distributed weather stations, the author extends previous work by focusing on hotter-than-normal years and the number of days exceeding thresholds of shaded wet bulb globe temperature (Wsd and Ysd WBGTs): white-flag-day ($\geq 25.6^\circ\text{C}$) and yellow-flag-day ($\geq 29.4^\circ\text{C}$). Results indicate that 27% of the sampled population resides in high-risk “red zones” with ≥ 10 yellow-flag days per year, where passive measures are unlikely to suffice. About 30% occupy “green-amber” zones with frequent white-flag-days but few yellow-flag-days, suggesting attention to vulnerability-dependent cooling needs. The 10-day exceedance criterion aligns with ASHRAE’s unmet-hour allowances, supporting its use as a design trigger. Findings highlight practical limits of passive strategies and the need for adaptive planning in regions approaching these thresholds. The caveat of this study is that if shaded breezy outdoor living areas would suffice to provide cool relief from a heat wave in a locality, then it is plausible that shaded and cross-ventilated buildings also could provide adequate indoor shelter from heat waves, whereas air-conditioning may be generally necessary elsewhere.

Keywords Climate; Heatwaves; Passive Cooling; Air-Conditioning; Public Health

1.0 Introduction

Life expectancy (1) and economic growth (2) in hot/humid climates have improved with the mass deployment of air-conditioning (3). The socioeconomic context is that mass adoption of air-conditioning has reduced heat stress in humid-hot climates, and so has the potential to facilitate economic productivity by reducing mortality and morbidity, and encouraging net migration. But neither traditional vernacular designs (4, 5), nor contemporary “bioclimatic” solutions (6) should be disregarded without reason. Depending on local circumstances some refrigerative air-conditioning may be necessary to complement more efficient modes of providing cool relief (7, 8). Yet the growing demand for air-conditioning can contribute to deadly power blackouts (9), such that air-conditioning becomes inoperable.

Wicked problems can be circumvented by “thinking outside the box”. The present work is framed in response to the modern paradigm shift to insulate buildings with the ambition of improving winter comfort without increasing demand for heating that could be provided by boilers or furnaces. Unintended problems can arise in summer as insulation traps heat and humidity from cooking and occupants’ respiration. So, the sub-tropical Australian State of Queensland’s sustainable development code (10) awards energy efficiency rating credits when a dwelling includes an outdoor living area covered from sun and rain, yet openly alfresco – such as a veranda. QDC only credits outdoor living areas if they are directly accessible from indoor space (lounge, kitchen, or dining room) and fully covered by an impervious roof. Additional energy

efficiency rating credits are awarded if the outdoor living area is covered by a ceiling fan suspended below an insulated roof.

Australian governments (including Queensland) require dynamic simulations of new building designs that assess both the heating and cooling loads within the building envelope (11), and such software has the potential to assess overheating risk indoors (12). Subsequently the UK Government has introduced building regulations to encourage external shading of windows and cross flow ventilation in preference to air-conditioning – complicated by demands to improve standards of insulation in order to minimize demand for heating in winter (13).

Naturally ventilated buildings and sheltered outdoor living areas such as balconies and verandas (14, 15) may provide some relief when air-conditioned buildings fail to provide resilient cooling during extreme heatwave events or power grids failures (16). So the present work aims to map the global bioclimatic limits of passive and low energy alternatives to air-conditioning, based on ground-truth observations, and to consider local trends. Accepting that there may be poorly designed dwellings prone to dangerous overheating that demands air-conditioning while neighbouring parks and gardens may provide passively cool relief – the current work uses a readily computed measure of heat stress to identify the practical limit of shaded outdoor living areas as an alternative to air-conditioning. Basically to think outside the building envelope, yet under shade.

The geographical focus of the present study is global, as CIBSE members work in a range of cooler and hotter climates, ranging from UK, Ireland, and New Zealand to Australia, Hong Kong, and Middle East. So as to discount undeveloped outposts, the internationally accredited network of weather stations can each be assigned a weighted “vote” by considering their coincident population, such as the one square km gridded population of the world 2000-2020, GPWv4 (17). Outdoor living areas from Queensland Australia illustrate humid-tropical problem solving, while developments from the UK demonstrate adaptation in a temperate climate. In either case, it is reasonable to assess if air-conditioning might be avoided – if well ventilated buildings or sheltered outdoor living areas could provide cool relief during heat waves.

5.1 Wet bulb globe temperature (WBGT) and heat stress flag categories

Consider a counterfactual approach to design of air-conditioning by considering passive and low energy alternatives, following global place-based analysis of which heating and/or cooling systems may be appropriate (18). That research commenced by assuming air-conditioning is desirable, as suggest in peer-reviewed paper from ASHRAE’s 3rd international conference convened in the Middle East (19). The criteria for direct expansion vapour compression cooling being when mean daily outdoor air conditions rise above 24°C dry bulb temperature or 9.4 °C wet bulb temperature – except for conditions when lower energy cooling may suffice (not exceeding 27°C dry bulb or 24 °C wet bulb). That complex threshold was found in the more recent study (18) to not exceed 25.6°C wet bulb globe temperature in shade at the time of daily maximum (WBGT_{smax}).

25.6°C (78°F) WBGT is the lowest threshold (Table 1) used in military and athletic settings to assess environmental heat stress and determine safe activity levels, which triggers a “White-flag” warning – when healthy individuals can safely exert

themselves as long as they can rest in shade and remain hydrated, while older or unhealthy people should still be more concerned. A “Yellow-flag” heat stress warning is declarable if wet bulb globe temperature rises above 29.4°C (20), which is when “moderate risk” precautions (such as rest breaks and rehydration) become more important in the management of risk of heat-related illnesses (21). Military guidelines exclude “white-flag” from heat stress categories and rather lower their threshold for “green-flag” conditions to 26.7°C (80°F).

White ≥ 78°F 25.6 - 27.7°C	Green ≥ 82°F 27.8 - 29.4°C	Yellow ≥ 85°F 29.5 - 31.1°C	Red ≥ 88°F 31.2 - 32.1°C	Black ≥ 90°F 32.2°C -
very low risk	low risk	moderate risk	high risk	extreme risk
US military training guidance based on wet bulb globe temperature (21).				

Table 1: Thresholds of White-, Green-, Yellow-, Red-, and Black-Flag WBGT

WBGT is defined by equation 1.

$$\text{WBGT} = 0.7 \times \text{natural wet bulb} + 0.2 \times \text{globe temperature} + 0.1 \times \text{dry bulb} \quad (\text{eqn 1})$$

Where natural wet bulb is the temperature that a thermometer reads when the bulb is wrapped in a wet wick exposed to the micro-climate’s air flow (or stagnation as the case may be).

WBGT being most weighted by natural wet bulb readings, reflects local airflow conditions. In well-ventilated shade, natural wet bulb closely approaches the fully aspirated psychrometric wet bulb calculated from humidity and pressure. Well-designed shelters and shade trees can provide micro-climates where in the WBGT improves by eliminating both solar and thermal radiation while natural wet bulb temperature drops to approach aspirated psychrometric wet bulb temperature. Therein the shaded wet bulb globe temperature (WBGTs) given by equation 2.

$$\text{WBGTs} = 0.7 \times \text{psychrometric wet bulb} + 0.3 \times \text{dry bulb air temperature} \quad (\text{eqn 2})$$

WBGTs is readily computed from the annuals of meteorological observations, so we can determine where extreme heat and humidity have exceeded assumed safe threshold values (18). The policy of raising a yellow flag whenever WBGT breaches 29.4°C (85°F) has for half a century required officers to dismiss unacclimated recruits from training in dangerous heat (25). Meanwhile acclimated healthy soldiers could continue with a cycle of hydration and rest breaks, while activities were further limited when a red-flag heat stress warning was raised if WBGT breached 31.1°C (88°F).

A high-humidity example of red-flag conditions is 34°C shaded dry bulb (operative temperature) while wet bulb temperature is 30°C. Berkley Comfort Tool <https://comfort.cbe.berkeley.edu/> (26) suggests this particular breach of what we are considering “red flag” conditions corresponds to 75% relative humidity, and that ISO 7730 (27) predicted mean vote (PMV) would be 1.47 with 49% percent of population dissatisfied (PPD) – subject to 4 m/s air speed with local control for persons lightly dressed (0.36 clo) and resting (1 met). According to the same website (26) entering a 33% relative humidity breach of red-flag conditions (41°C dry bulb / 27°C wet bulb) with the same air-flow and lightly dressed resting scenario results in 3.52 PMV with 100% PPD – uncomfortably hot, but such hot-dry conditions are readily mitigated by spray misting (28) if fresh water is available.

International Standard ISO 7243:2017 (29) assesses thermal stress of indoor and outdoor environments, depending on metabolic rate of activities and acclimation of workers on the basis of Wet Bulb Globe Temperature (WBGT). Protective clothing can trap heat and humidity, elevating risk (Annex F of ISO 7243:2017) several degrees below what a safe WBGT would otherwise be. Rehydration being necessary for healthy evaporative cooling via sweat glands, individuals suffering from anhidrosis (either genetic or a side effect of certain drugs/medications) are unable to sweat, and thus limiting thermoregulatory ability. Without reference to flags or colour codes, Annex A of ISO 7243:2017 lowered thresholds for unacclimated people exercising at “low metabolic rate” (150 Watts) slightly to 29 °C WBGT, while acclimated persons are limited to 30 °C WBGT. But ISO 7243 “does not take account of any effect related to body size or similar characteristic, e.g. obesity, height, weight”. Table 2 summarises effective WBGT_{eff} as informative guide for local policy makers, where they state that “values will generally differ by ± 1 °C”.

Descriptive ISO Class	Metabolic Watts	acclimated WBGT_{eff}	unacclimated WBGT_{eff}	comparable flag colour
4 Very high	520	25 °C	20 °C	
3 High	415	26 °C	23 °C	~ White
2 Moderate	300	28 °C	26 °C	Green-Yellow
1 Low	180	30 °C	29 °C	Yellow-Red
0 Resting	115	33 °C	32 °C	Red-Black
Adapted from Annex A, ISO 7243:2017 (29) Table A.1				Refer Table 1

Table 2: ISO 7243 WBGT_{eff} thresholds for work at various metabolic rates

Passive survivability during heat wave power blackouts can be certified (30) by psychrometric analysis of temperature, humidity and thermal radiation if dwellings' WBGT doesn't exceed 28°C. Such conditions mostly coincide with white-flag heat stress conditions and only fractionally overlap green-flag conditions (21). Meanwhile, passive survivability of non-residential buildings is recognized for yellow-flag conditions up to 31°C WBGTs (30). A tenth of degree above is the threshold of outdoor conditions announced by raising a red-flag at athletic and military training facilities (31), in which case occupants would be advised to cease activities and seek cooler relief.

Intermediate preventive measures (breaks with refreshments) are recommended for lightly dressed activities during green-flag conditions when WBGTs breach 27.8°C (82°F), but un-fit and non-acclimated individuals should (32) spend at least 50% of their shift repeatedly resting and rehydrating. The threshold of extreme risk for adapted healthy individuals (“black-flag” conditions) is 32.2°C (90°F) WBGT, which can result in uncompensable heat stress even while resting and rehydrating continuously in shade (33).

5.1 Threshold of the tenth hottest day in a year

This study adopts the criteria that yellow-flag heat stress conditions (29.5 to 31.1°C WBGT) are undesirable but occasionally tolerable up to 10 days in a summer if precautions are implemented. This assumption aligns with ISO 7243 screening thresholds for acclimated individuals (30 °C WBGT) and U.S. military ‘yellow-flag’ guidance (29.5 °C WBGT), which recommend activity modification and cooling

measures under these conditions (20). Occupational studies reviewed non-fatal morbidity incidents at 29 °C WBGT, but recommended screening from 29.4 Heat Index (34) being about 25.6°C WBGTs, – which the current study adopts as the ‘white-flag’ threshold to justify air-conditioning for comfort and productivity.

Where ten or more shaded yellow-flag days (WBGT_{max} ≥ 29.5°C) are expected in years that are hotter than normal, then this is a place where access to air-conditioning or other means of active cool relief may be critical for public health and safety. Hotter-than-normal was defined in Australia during the 20th century by adding one standard deviation of the inter-annual variability to the year-on-year average of the tenth highest daily maximum (35), adapted in the current study by annual count of the number of days that maximum daily WBGTs equals or exceeds 29.5°C (78°F). Furthermore, since the climate of the 21st century is changing, the latest (circa year 2020) estimate of the mean added to the standard estimate of error of the interannual variability substitutes for the sum of the average and standard deviation at locations where the previous study established a statistically significant trend. If there is no statistically significant trend in the local annals of observations, then the sum of average and one standard deviation of the interannual variability is better than ignorance.

Meanwhile, vulnerable individuals may have a legitimate need for relief from white-flag conditions – at a threshold of 25.6°C WBGT (21) in shade. The current research focuses on reanalysis of locations that experienced more than 10 white-flag days in a hotter-than-average year, but not more than 10 yellow-flag days in a hotter-than-normal year. This subset of the global array of GSOD-recognised weather stations as analysed during the years 1988-2020 is hereby referred to as the “green-amber” subset, as there were numerous green-flag and yellow-flag days during hot years.

White-flag exposure up to nine days per annum only occasionally breached into green-flag conditions (27.8 to 29.4°C WBGT) - coinciding with Table 2 which outlines recommendations for unacclimated healthy individuals to rest while acclimated individuals should moderate their exertion. Yellow-flag exposure inherently includes breaches of green-flag exposure, so the two have been lumped together for reanalysis of observations 1987-2020.

5.1 Objectives of the Current Study

The current study embarks on reanalysis to extend identification of where public access to air-conditioned shelter may be necessary - beyond what was taken from average exceedances of 10 days per year during the period 1988-2020 (18). Another innovation of the present work is delineation of ranked overheating risk classification of the 16,582 weather stations where local bioclimatic predilections for rebalancing the heating and cooling of buildings were initially analysed (36). The current study specifically aims to identify locations where shaded outdoor WBGTs exceed thresholds that challenge passive cooling strategies, and according to individual vulnerability. So, the current study reassesses the output of the previous study (36), with maps and aggregated statistics defined by seven thresholds in order of descending risk of heat stress (5, 4, 3½, 3, 2, 1, 0), that depend on the number of WsD† white-flag-days (WBGTs ≥ 25.6 °C) or YsD† yellow-flag-days (WBGTs ≥ 29.5 °C) days in a hotter than normal summer as follows: (5) Highest risk (10≤YsD†); (4) Higher Risk (3≤YsD†); (3½) Medium High Risk (1≤YsD†); (3) Medium Low Risk (10≤WsD† and YsD†<1); (2) Low Risk (3≤WsD†); (1) Lower Risk (1≤WsD†); (0)

Lowest Risk ($WsD_{\dagger} < 1$) – where $\dagger$ denotes distinction that the new thresholds apply to hotter than average years.

2.0 Materials and Methods

Meteorological observations were downloaded from the Integrated Surface Database (ISD) Global Summary of the Day (GSOD), which is a global database that consists of surface observations archived at the NOAA's National Centers for Environmental Information (NCEI) (37, 38). GSOD (39) is a data collection which summarizes daily weather elements computed from ISD data. Daily weather summaries include mean values of temperature, dew point temperature, and station pressure, as well as maximum and minimum dry-bulb temperature. ISD and GSOD undergo quality controls to remove errors that might be present among original observation data from thousands of meteorological stations around the world since 1973. There were 12,159 station summaries during year 2024, having increased from 8,418 during year 1975 with a peak of 12,262 during year 2020. Some stations have commenced observations later, while others closed during the half century 1975-2024, which intersected over 21,000 locations. But some of these stations' data were of insufficient quality and/or resolution to evaluate annual count of days of WBGTs exposure. For example, it is impossible to determine wet-bulb (nor WBGT) without records of relative humidity or dew point, and an annual rate was not considered without at least 300 days of both dry- and wet-bulb observations. The final list of GSOD stations included 16,582 sites, which were more sparsely distributed among developing countries. The scatter of density can be judged in the earlier study (18, 36) or by inspection of the maps presented in the results of the current study – except that sites without any observation of any single white-flag day are suppressed from the maps below.

5.1 Re-evaluation of results of global analysis of 34 years through 2020

Prior to additional procedures that revisit GSOD (39) to produce half-century (1975-2024) annals of the green-and-amber site subset selection from the published summary tabulations of the 34 years 1988-2020 (36). Further research will focus on the “green-amber” subset of weather stations for which the 34-year analysis had $WsD_{\dagger} \geq 10$ but $YsD_{\dagger} < 10$, using MATLAB script “green_amber.m” (supporting on-line material). In summary this script provides a series of procedures as follows:

1. Import climate metrics from the previous study (36)
2. Classify stations by thresholds of WBGTs-based hot days in hotter years (e.g., WsD , YsD)
3. Define “green-amber” sites where $WsD_{\dagger} \geq 10$ but $YsD_{\dagger} < 10$ (frequently hot, not extreme)
4. Categorize colour-coded risk bins from lowest up to high risk (cyan, blue, green, amber, red)
5. Plot categorized station data on scatter and geospatial figures.

Locations were classified by looping (incrementing subscript i) through the full station list of the 34 year annals, and for the example of the green class (less risky part of the green-amber group), by testing if (both $WsD\uparrow_i \geq 10$ as well as $YsD\uparrow_i < 1$ are true), or if $1 \leq Ysdi < 3$. This selected stations where moderate “white-flag” WBGT exposure ($\geq 78^\circ\text{F}$) occurred at least 10 days p.a., but also where “yellow-flag” WBGT exposure ($\geq 82^\circ\text{F}$) occurred less than 3 days p.a. The “yellow” classification is applied if the average number of yellow flag days was less than ten, but greater than or equal to three ($3 \leq Ysdi < 10$). The script then drives mapping of seasonal stress exposure symbols denoting increasingly categories colour-coded as follows:

1. Cyan: “Lowest” mild exposure 0.01-0.99 days breaching “White-flag” WBGTs.
2. Blue: “Lower” exposure 1-1.99 days breaching “White-flag” WBGTs.
3. Green: “Medium-Low” exposure 3–9.99 days breaching “White-flag” WBGTs or 3½ Green “Medium-High” exposure 1-2.99 days breaching Yellow-flag”.
4. Amber: “Higher” exposure 3–9.99 days breaching “Yellow-flag” WBGTs.
5. Red: “Highest” exposure ≥ 10 days exposure breaching the “Yellow flag” WBGTs threshold.
0. Shape, where a star (☆) distinguishes a hotter-than-normal estimate $WsD\uparrow$ or $YsD\uparrow$ that broke through a higher colour-coded exposure category while a circle (○) denotes that long term historical average of Wsd or Ysd had the same colour category as $WsD\uparrow$ or $YsD\uparrow$ there.

Green-and-Amber locations that were reanalysed over the half-century ending 2024 are mapped in the results Figures 1-8 colour coded with green and amber symbols (1–2.99 & 3–9.99 “yellow-flag” days p.a.). Green-amber locations had medium-high exposure in a hotter-than-normal year, that could be tolerable without air-conditioning for healthy adapted individuals resting in breezy shade as long as they are provided with hydration refreshments.

One criterion for excluding stations from further reanalysis was prior classification as high-risk, where shaded WBGT exceeded the yellow-flag threshold ($\geq 29.5^\circ\text{C}$) on ten or more days in a year. These locations already have been established to require universal access to air-conditioning, so they fall outside the present study’s focus on identifying areas where passive or low-energy cooling might still suffice. These locations are mapped in the results section Figures 1-4 colour coded with red symbols (≥ 10 “yellow flag” days p.a.). It is not untypical that many of these stations experienced red-flag conditions, while some experienced black-flag conditions (especially where the number of yellow-flag-breaching-days far-exceeded 10 d/y).

The other criteria for not embarking on further reanalysis was if the 34 years ending 2020 concluded that the vicinity of any particular weather station had not experienced ten or more “white-flag” WBGTs-days in a hotter-than-normal year. These locations are mapped in the results section Figures 1-4 colour coded with cyan and blue symbols (1–2.99 and 3–9.99 “white-flag” days p.a.) are relatively lower and lowest exposure risks for healthy adapted individuals who are able to take breaks to rest and rehydrate in breezy shaded conditions, while older people and more vulnerable individuals may require air-conditioning. The general population may also desire air-conditioning to maintain normal routines of comfortable productivity during summer.

3.0 Results

Table 3 details how there were n=3906 locations identified as the “green-amber” portion of the global n=16,582 weather station annals of the 34 years 1988 through 2020. This subset excluded “red-zone” locations where ' YsD†≥10 days in a hotter-than-average year, as well as cooler locations where WsD†<10 days in a hotter-than-average year. The “green-amber” subset had a coincident gpw_v4 population (40) of 2,783,598 out of 9,124,984 population dwelling coincidentally within the same grid cells as the global network of weather stations. Hence the “green-amber” subset represents 30.5% of global population sample, biased by coincidence with WMO weather stations.

Exposure Risk Categories 1987-2020	stations	gpw_v4_pop	vote
average years' Ysd≥10 (highest risk "5")	n=1,323	1,867,276 p	20 %
“red zone” hot year's YsD†≥10 (highest risk 5)	n=2,078	2,491,040 p	27%
average years' Ysd≥3 (higher risk "4")	n=1,167	950,994 p	10%
“amber zone” hot year's YsD†≥3 (higher risk 4)	n=1,368	950,994 p	10%
average years' Wsd≥10 (medium risks "3 &	n=2,740	1,977,525 p	22%
“green zone” hot year's WsD†≥10 (medium	n=2,713	1,748,335 p	19%
average years' Wsd≥3 (lower risk "2")	n=1,436	784,210	9%
“blue zone” hot year's WsD†≥3 (lower risk 2)	n=1,590	807,224 p	9%
average years' Wsd≥1 (lowest risk "1")	n=1,537	873,174	10%
“cyan zone” hot year's WsD†≥1 (lowest risk 1)	n=1,353	695,259 p	8%
average years' Wsd<1 (lowest risk "0")	n=7,949	2,588,218 p	28%
hot year's WsD†<1 (lowest risk 0)	n=7,050	2,151,368 p	24%
stations NOT reporting 2020 WsD†'s/YsD†'s	n=430	83,586 p	0.9%
totals	n=16,582	9,124,984 p	100%

Table 3: Map Key of Marker Colour Code Exposure Risk Categories 1987-2020

There was no overheating risk ($WsD† < 1$) at 7,050 stations coincident with 24% of the population that are not plotted on the maps. Maps employ cyan and blue coloured symbols to denoted white-flag risk ($1 \leq WsD† < 10$) at 2,943 stations coincident with 17% of the population. Increased overheating risk is plotted with green and amber symbols ($10 \leq WsD†$ while $YsD† < 10$) at 4,081 stations coincident with 30% of population. Red symbols denote where exposure to humid overheating was highest ($10 \leq YsD†$) at 2,078 stations coincident with 27% of the population.

Results are summarized in Figures 1-4 as maps with scatter-plot symbols which are shaped and coloured according to Table 4. Meteorological stations that did not breach any of these criteria or where annals were of insufficient quality to interpret are not plotted. Note that urban heat islands are rarely monitored by long term meteorological observations, and so heat stress is likely to be worse in urban centres than the surrounding datapoints indicate. $WsD†$ represents the number of days in a hotter-than-normal year that “white flag” conditions were breached, while Wsd represents the number of days breached in an average year. Likewise, $YsD†$ represents the number of days in a hotter-than-normal year that “yellow flag” conditions were breached, while Ysd represents the number of days breached in an average year. There are five map colour classifications as set out in Table 4.

Colour	Stars ☆ hot years	Circles ○ average	coloured symbol risk category	Seasonal Exposure
Cyan	$1 \leq WsD\uparrow < 3$	$1 \leq Wsd < 3$	“white flag” WBGTs 25.6 to 27.7°C possible 1 up to 3 days pa	1 Lowest
Blue	$3 \leq WsD\uparrow < 10$	$3 \leq Wsd < 10$	“white flag” WBGTs 25.6 to 27.7°C possible 3 up to 10 days	2 Lower
Green	$10 \leq WsD\uparrow$	$10 \leq Wsd^*$	“white flag” WBGTs 25.6 to 27.7°C possible 10 or more days, but less than 3 yellow-flag days. May include green-flag WBGTs.	3 Medium
Amber	$3 \leq YsD\uparrow < 10$	$3 \leq Ysd < 10$	“yellow flag” WBGTs 29.5 to 31.1°C possible 3 up to 9 days pa	4 Higher
Red	$10 \leq YsD\uparrow$	$10 \leq Ysd$	“yellow flag” WBGTs 29.5 to 31.1°C on 10 or more days pa. May include red-flag WBGTs.	5 Highest

Table 4: Map symbol shape and colour classifications according to WBGTs

Per annum (“pa”) classifications account for exposure in hotter-than-normal years. Herein star shaped symbols ($WsD\uparrow$ and $YsD\uparrow$) denote where the addition of one standard deviation above interannual average (Wsd and Ysd) or standard estimate of error added to linear regression trend to the last year increased map colour classification thresholds in hotter-than-normal years. Otherwise, circle symbols denote where interannual average (Wsd and Ysd) share the same map colour classification as hotter-than-normal years ($WsD\uparrow$ and $YsD\uparrow$).

Cyan stars and circles indicate where WBGTs in shade were expected to have reached “white-flag” conditions one or two days pa. Cyan might represent where only the most vulnerable individuals require active cooling relief, while most others would cope by resting in well-ventilated shade.

Blue stars and circles indicate where WBGTs in shade were expected to have reached “white-flag” conditions three to nine days pa. Blue might represent where a larger proportion of elderly or unhealthy individuals could benefit from active cooling relief during extreme heat events.

Green stars and circles indicate where WBGTs in shade were expected to have reached “white-flag” conditions ten or more days pa among which one or two reached into “yellow-flag” conditions. These locations experience a number for days including “green-flag” conditions. Green suggests where most healthy individuals could cope with heat by staying in shade and regularly rehydrating.

Amber stars and circles map markers indicate where WBGTs in shade were expected to have reached “yellow-flag” conditions three to nine days in a hotter than normal year. Yellow map markers suggest where a smaller proportion of healthy adapted individuals might be able to cope without air-conditioning if they can regularly rest and rehydrate under breezy shade, while green map markers indicate where there were fewer “yellow-flag” days – yet numerous “green-flag” days.

Red stars and circles indicate where WBGTs in shade were expected to have reached “yellow flag” conditions ten or more days pa, without specifying if “red flag” conditions were reached. Many locations indicated by red symbols suffered many days of “red-flag” conditions, and not excluding the possibility of instances of “black-flag” WBGTs conditions. This is the highest exposure risk classification, which is mapped as the “red-zone”.

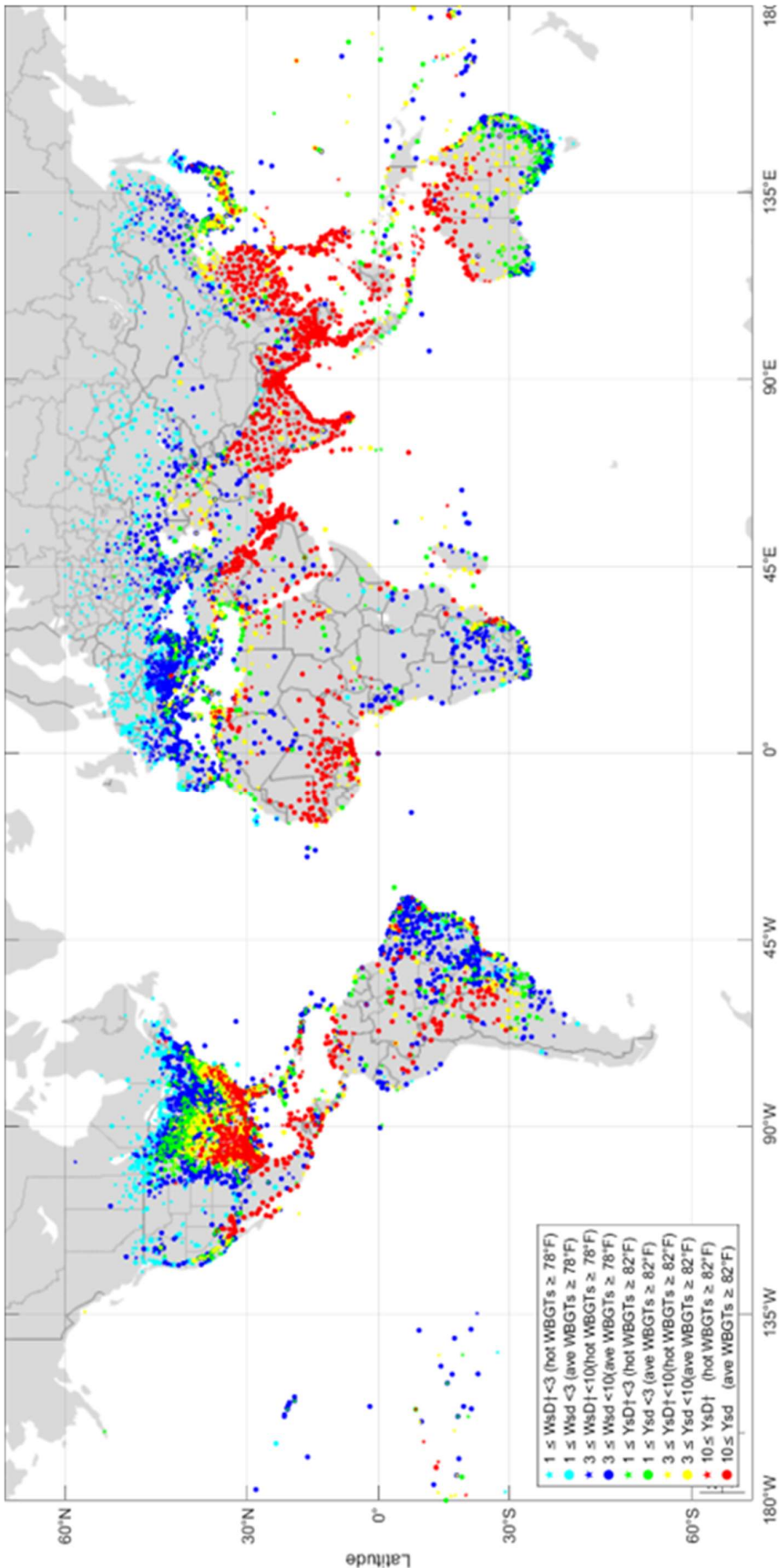


Figure 1 – Global map classified by Table 4.

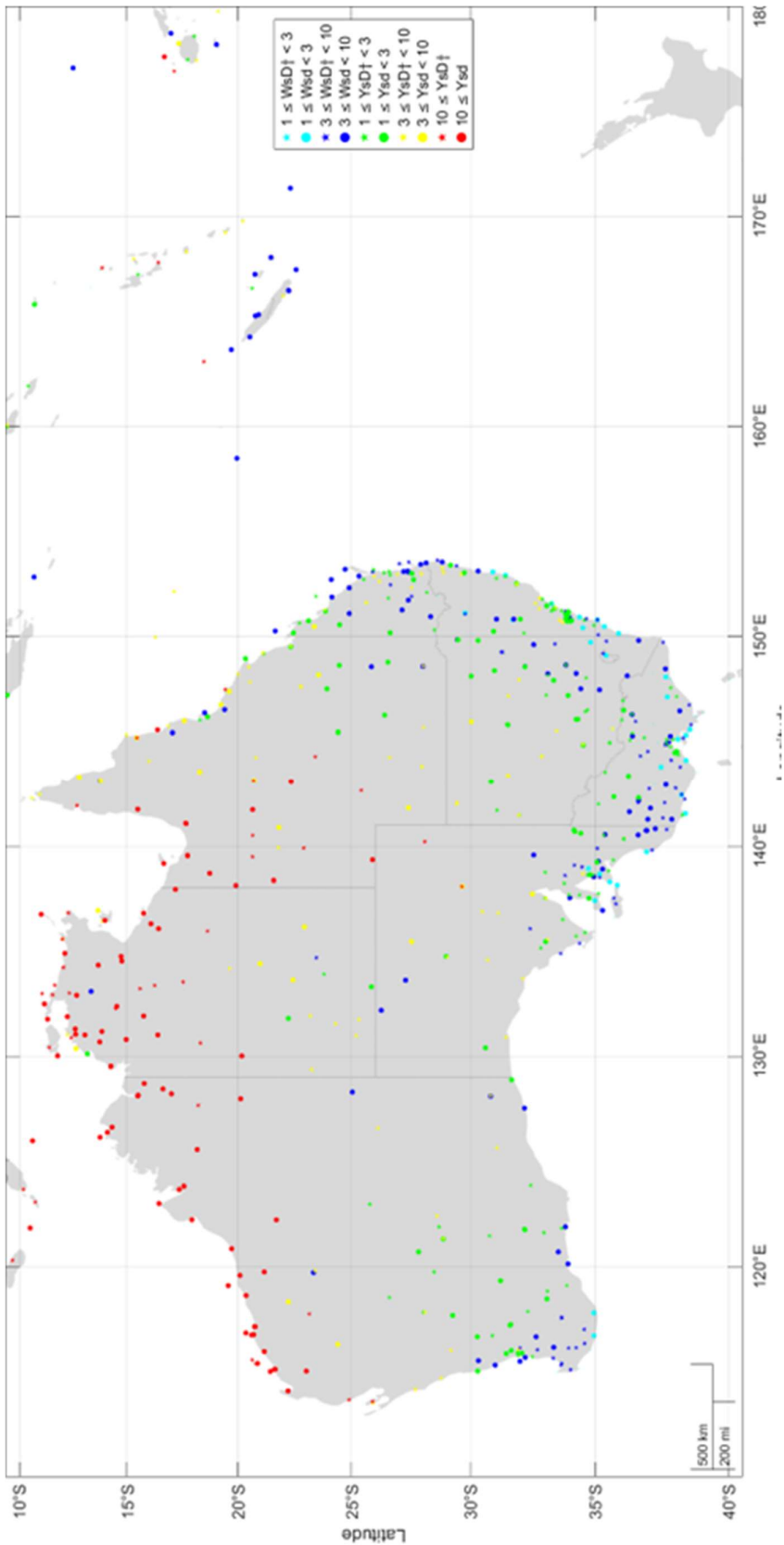


Figure 2 – Australia & New Zealand classified by Table 4.

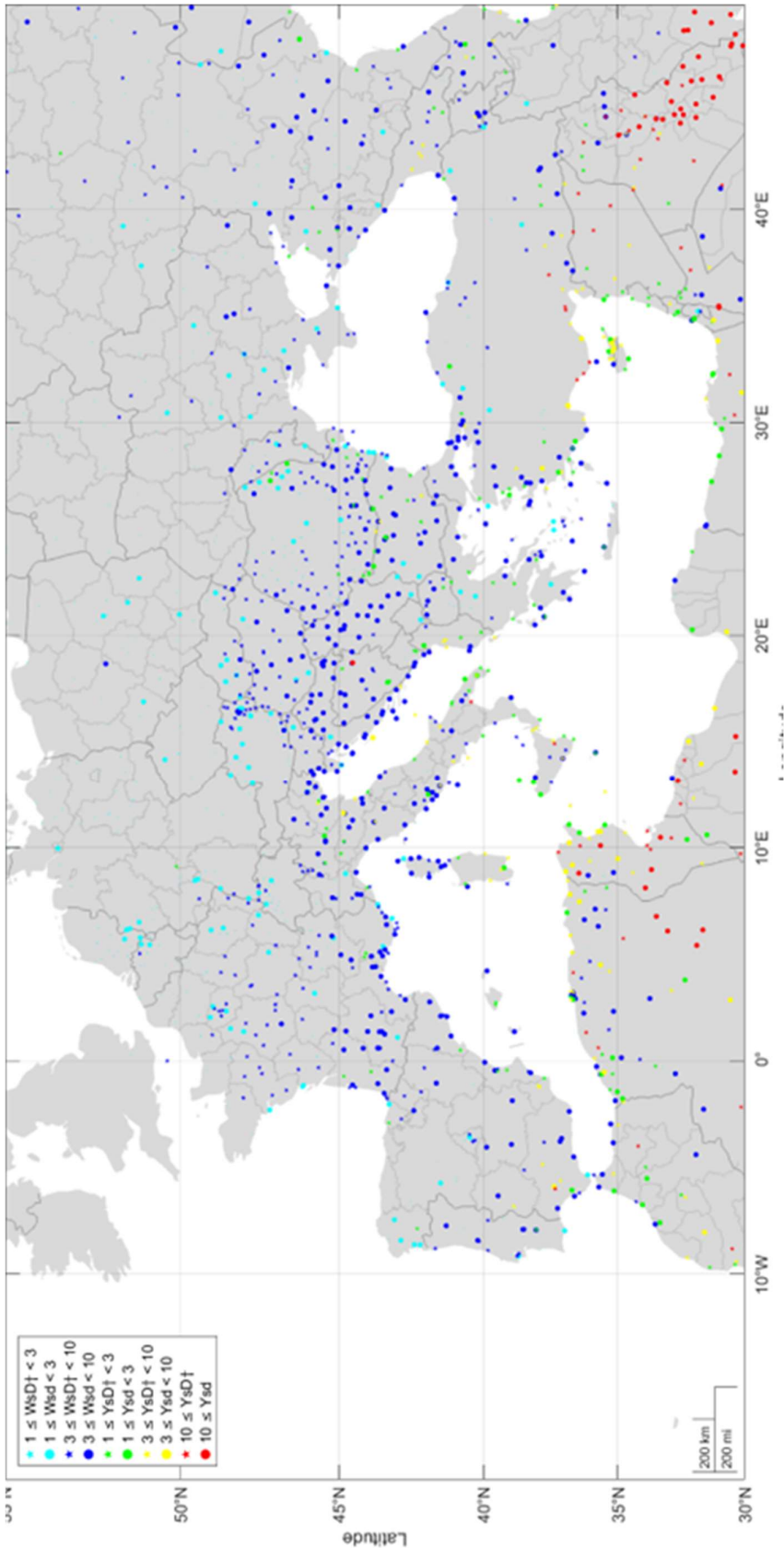


Figure 3 – Mediterranean classified by Table 4.

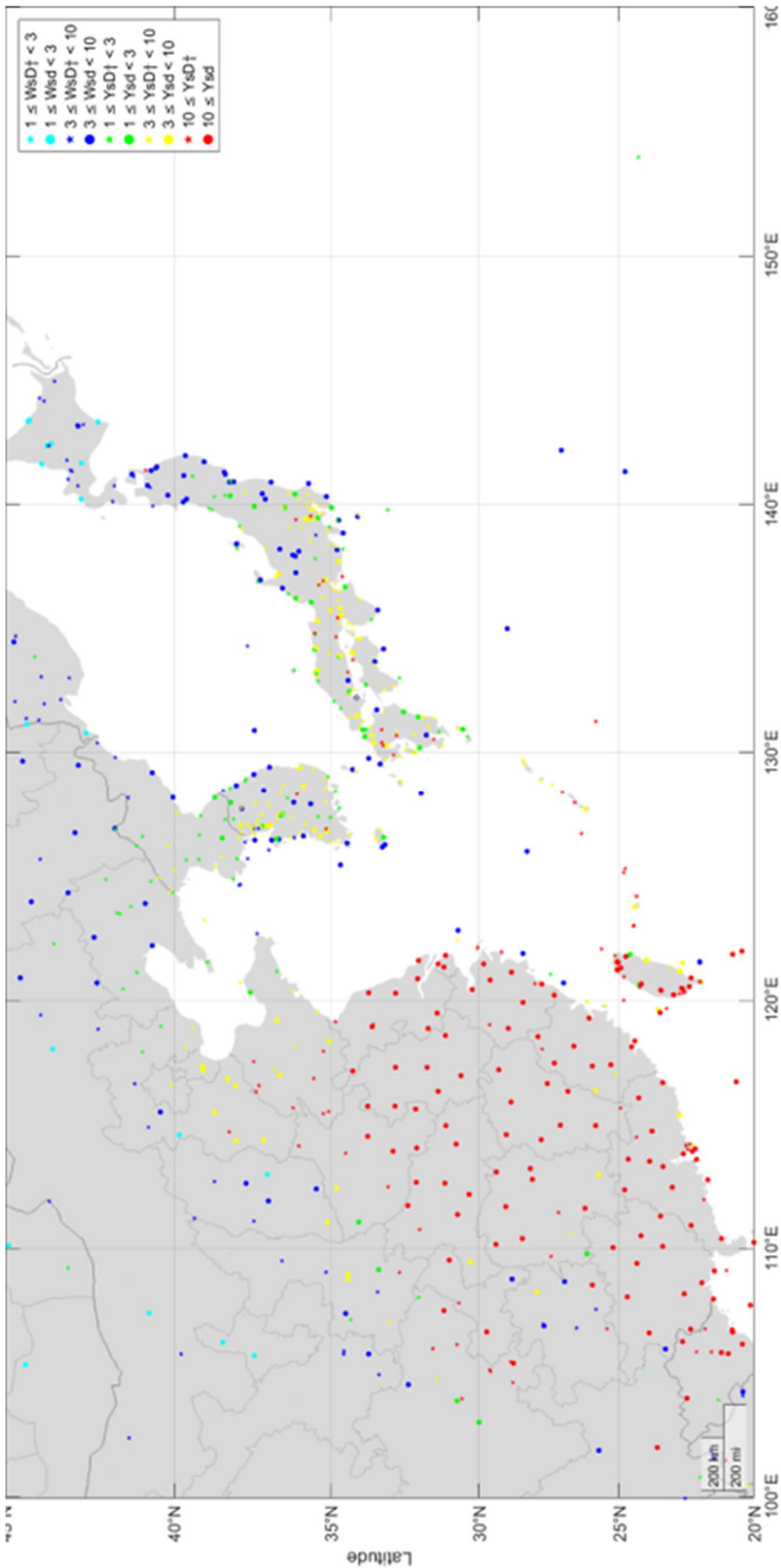


Figure 4 – East Asia classified by Table 4.

Figures 1, 2, 3, and 4 are geographical maps that colour classify seasonal exposure during hotter years at previously analysed locations based on the annals of observations 1988 through 2020 (36).

Red circles plotted on Figures 1,2,3 and 4 denote locations which were concluded to require access to air-conditioning for all persons (18) based on a long term average of ten or more “yellow flag” days per year (1988-2020). Additional red stars represent additional places where there were at least ten such days in hotter-than-normal years during that same period. Distinction amongst star and circle shapes is clearer in Figures 2, 3, and 4 resolving observations in Australia, the Mediterranean, and East Asia. Within each colour-class, star shapes tend to appear at higher elevations and higher latitudes than their comparable circle-shaped counterparts.

4.0 Discussion

Interpretations reflect the author’s view of resilience and sustainable design rather than a public policy. The intention is to suggest an internationally understandable screening criteria for risk assessment of environments. The author is not aware of any standard defining which environments require that active cooling need be made accessible to all individuals. For example, as a Registered Professional Engineer of Queensland, the author asserts that there is no obligation to provide air-conditioning under the building and development codes of that quarter of Australia. But author acknowledges that there are critical process applications, poorly designed existing buildings that overheated, and also well-designed buildings where the occupants happen to be particularly vulnerable individuals who personally need air-conditioning in the same localities where passively cooled buildings have proven to be sufficient for other members of their local community.

Partially answering the question implied by the title of this paper, accessibility to air-conditioning during heat events may be a necessity for most members of the population inhabiting the highest risk area (denoted by red symbols). Meanwhile increasing proportions of population could have tolerated heat where risk was lower (decreasing risk from amber, green, and blue, to cyan in reference to the colour-coded symbols on the presented maps).

Urban heat islands are rarely monitored long-term with WMO-recognised meteorological stations. All too often there’s only an airport station in the vicinity of an unmonitored location where air-conditioning is essential. Consequently, perhaps it would be better to suggest that air-conditioning is essential in mapped “red zones” and also possibly in many urban contexts. In summary, the author’s view as a designer would be that air-conditioning (or another effective method of cooling) is essential in the red zone, and also needs to be considered in urban settings. Although defined by raising a yellow flag WBGTs ten days in one summer, some of those day the heat and humidity continue to rise into red-flag conditions (WBGTs $\geq 31.2^{\circ}\text{C}$) later in the day, and so are mapped as the highest risk “red zone”. The red-zone is thus found to have been inhabited by 27% of the global population sample, which may have missed significant urban heat islands where WBGTs exceed 29.4°C (yellow-flag conditions) for 10 or more days in a hotter-than-average year.

Passive adaption measures could be considered outside the red zone. Shaded breezy living areas could be retrofitted outside air-conditioned building envelopes to offer building survivability in the event of power failures. Buildings projects within

“green-amber” locations mapped in this paper could exploit dynamic simulations of overheating risk to design passive and low energy alternatives to air-conditioning if practical, while air-conditioning may be a reasonable default in the “red zone”. But there is a problem with dynamic simulations if climate continues to change, because typical meteorological files are based on historic data. The only on going work around to the aging TMYs that the author is aware of is Langley Research Center's Prediction Of Worldwide Energy Resources (47), also known as NASA POWER. Besides the forgoing discussion of where air-conditioning may be essential, the methodological criteria of allowing passive indoor or shaded outdoor living areas to float 10 days per year is discussed in further detail because there are few places on earth with many years of continuous hourly observations of the weather. Don't forget that building simulation models' single year of 8670 hour inputs are synthetic conglomerates, while the GSOD datasets provide decades of continuity.

5.1 Exceedance of a threshold 10 days per year is comparable to ½ % of the 8760 hours in one year

Previous research (18) argued that public access to air-conditioned shelter is essential in places where the daily maximum wet bulb globe temperature outdoors under shade (WBGTs) exceeds 29.4°C (the lower threshold of yellow-flag conditions) no more than ten days per year. Now the current discussion reconsiders if this measure of duration is comparable to building simulation and design practice for indoor temperatures to be allowed to float above an air-conditioning control setpoint 50 hours per year. The ten days per year allowance was inspired by the 20th century Australian method of design of air-conditioning based on whatever maximum daily outdoor temperature is not exceeded more than 10 days per year (41) under the condition that air-conditioning design thresholds should be “inclusive of one standard deviation”. Assuming a normal distribution of year-to-year variability, such thresholds tend to cover 84% of the annals of meteorological observations. And so, it turns out that Australian outdoor air temperatures were exceeded only about 5 days per year on average over the years of observations so that there were very few years when that design temperature would exceed more than 10 days in any particular “hot” year. This is similar to the threshold of five days of indoor dry bulb exceeding setpoint before people tend to install air-conditioning (42).

Accepting tolerance in specifying air-conditioning design conditions reduces capital cost and operating costs, by allowing justifiably necessary cooling installations to operate more efficiently for most of the time they are in service. This causes a few “unmet hours” on occasions when the indoor temperature may float above the desired thermostatic setpoint. ASHRAE Energy Standard 90.1 (43) allows building design simulation results with up to 300 unmet hours per annum. These issues have been explored (44) while others found dramatically increasing exceedance in future projections (45). Breaching a threshold on the hottest 10 days in a year at the time of the afternoon maximum does not determine 240 hours of exceedance (24 hour/day × 10 days). The diurnal cycle is well-modelled with the “4 + 4 +4 rule” (46) finding only four hours (noon through 4 pm) near daily maximum, while four hours are usually near the daily mean (rapidly rising 8 am through 10 am and rapidly falling 6 pm through 8 pm), while another four hours tend to be near an average of the daily mean and maximum (rising 10 am through noon and falling 4 pm through 6 pm).

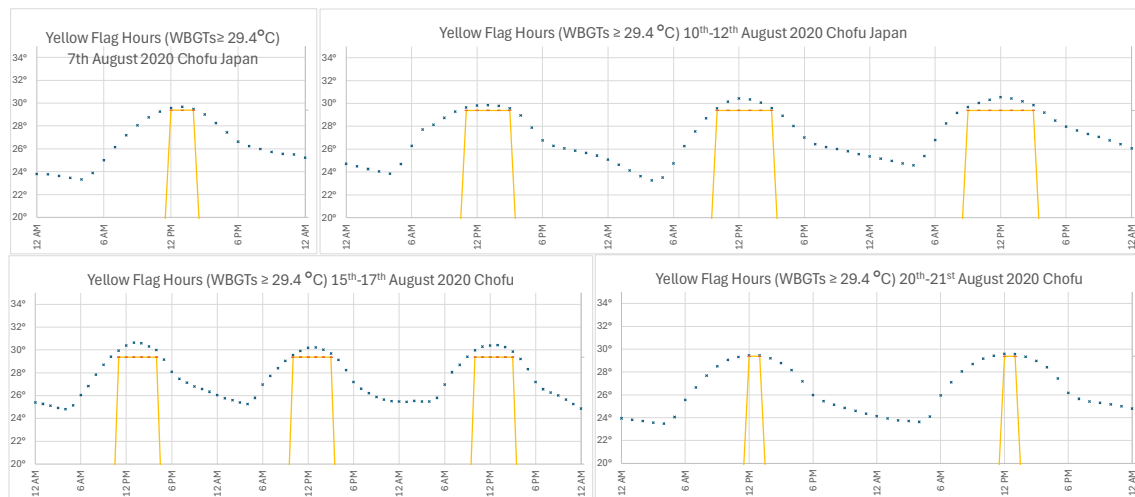


Figure 5 – Hours / days exceeding 29.4°C WBGTs (yellow flag threshold) Chofu Japan year 2020.

Figure 5 provides an example of diurnal curves breaching the yellow-flag threshold, where WBGTs was generated using Langley Research Center's Prediction Of Worldwide Energy Resources (47) downscaled model of hourly drybulb and wetbulb temperatures 2 meters above ground in the vicinity of Chofu Airport in Tokyo, Japan during year 2020. In this example there was a breach of the “yellow flag” WBGTs threshold 43 hours, being only during 9 days in year 2020. So, the number of exceedance hours varied from 2 to 7 during the 9 yellow-flag days of year 2020. Four years later the yellow-flag threshold was breached 147 hours, on 35 days in year 2024. There were also 3 red-flag WBGTs threshold breaches in 13 hours during the hottest days that year (7th, 8th and 20th July 2024).

In the 2020 example Chofu averaged about 4.8 hours per day of yellow-flag breaches, and about 4.2 hours per day of yellow-flag (or worse) breaches in 2024. Together with the “4 + 4 + 4 rule” (46), when and where any particular threshold is only breached 10 days in a year, these conditions are not expected to persist more than 40 or 50 hours per year (about ½ % of the 8760 hours in one year).

5.0 Conclusions

Passive and low-energy cooling strategies are limited by the environment

While passive building designs and shaded outdoor living areas can mitigate heat stress under green- and yellow-flag conditions ($27.8^{\circ}\text{C} < \text{WBGTs} \leq 31.1^{\circ}\text{C}$), such shelters may be insufficient under an extended series of yellow-flag events. Passive survivability without air-conditioning is feasible for most of the population dwelling outside of the “red-zone” or urban heat islands, while vulnerable individuals may need cooling.

The “green-amber” subset should be monitored for local climate change.

30% of the global sample population dwell at 4,081 “green-amber” locations—where white-flag conditions were breached at least 10 days in a hotter-than-average year – while there were less than 10 yellow-flag days. These areas may not yet require universal air-conditioning, but monitoring and forecasting is warranted to check if some of these places join the “red zone”.

Ten exceedances of daily maximum are comparable to 50 unmet hours.

The tenth hottest day in a hotter-than-average year exceeding a threshold aligns with indoor unmet hour allowances (e.g., ASHRAE 90.1's 50 hours per year). This supports the validity of expecting a series of ten or more daily maximum exceedances as a design trigger point.

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