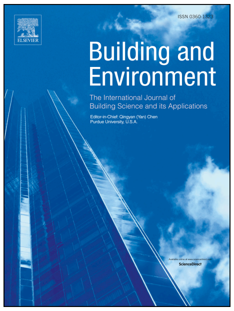

Climatic applicability of downdraught evaporative cooling in the United States of America

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PII: S0360-1323(18)30174-4
DOI: 10.1016/j.buildenv.2018.03.039
Reference: BAE 5373

To appear in: *Building and Environment*

Received Date: 14 February 2018
Revised Date: 23 March 2018
Accepted Date: 24 March 2018

Please cite this article as: Aparicio Ruiz P, Schiano-Phan R, Salmerón-Lissén JoséManuel, Climatic applicability of downdraught evaporative cooling in the United States of America, *Building and Environment* (2018), doi: 10.1016/j.buildenv.2018.03.039.

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The potential for application of downdraught cooling in the United States of America (U.S.) depends on its climatic characteristics. However, due to the large geographic span of the country, it varies due to differences in latitude, and a range of geographic features influencing climate, including altitude, topography and terrain. This study describes the development of climatic applicability maps of downdraught cooling in the U.S., which can aid designers in the initial identification of the correct cooling strategy for the geographic area of interest. The proposed approach is based on a set of maps, which are derived from two related climatic indexes: dry bulb temperature to wet bulb temperature depression (DBT−WBT), representing the climatic opportunity, and 26ºC minus wet bulb temperature (26ºC−WBT), representing the climatic opportunity against the theoretical cooling requirement for each location. The downdraught cooling strategy and degree of applicability is classified in the map, based on the aforementioned climatic and cooling parameters. Finally, four representative buildings in four different regions with different climatic conditions were selected for climatic analysis. This resulted in the identification of some climate zones for downdraught cooling application in the U.S. and the suggestion of appropriate design strategies for each of them.

Keywords: climatic applicability; downdraught cooling; dry bulb temperature; passive downdraught evaporative cooling; wet bulb temperature

1. Introduction

The building sector accounts for a significant part of the global energy consumption. For decades, space heating and cooling (space conditioning) accounted for more than half of all the residential energy consumption [1]. In recent years, further progress has been made in the identification and implementation of energy demand reduction strategies in buildings. This trend was created by an increased adoption of more efficient equipment, better insulation, more efficient windows, and population shifts to warmer climates [2]. This shift in how energy is consumed in homes has seen that even if per-household energy consumption has steadily declined, more homes are using air-conditioning than in the past.

According to the U.S. Energy Information Administration (EIA), the Residential Energy Consumption Survey [3], nearly 9 out of 10 U.S. homes are air conditioned by central units, individual units, or both. On the other hand, other solutions, including use of fans, dehumidifiers, and pool pumps, also increase summer electricity use in homes. In the U.S., the monthly electricity consumption peaks are in July and August when temperatures and cooling demand are the highest. The EIA estimates that 18% of annual household electricity use are for air conditioning. Three-quarters of all air-conditioned homes use central equipment, but individual air-conditioning units are more common in the cold to very cold climate regions in the northern United States and the marine climate region along the West Coast. In Figure 1 the use of this systems is shown by climatic regions.

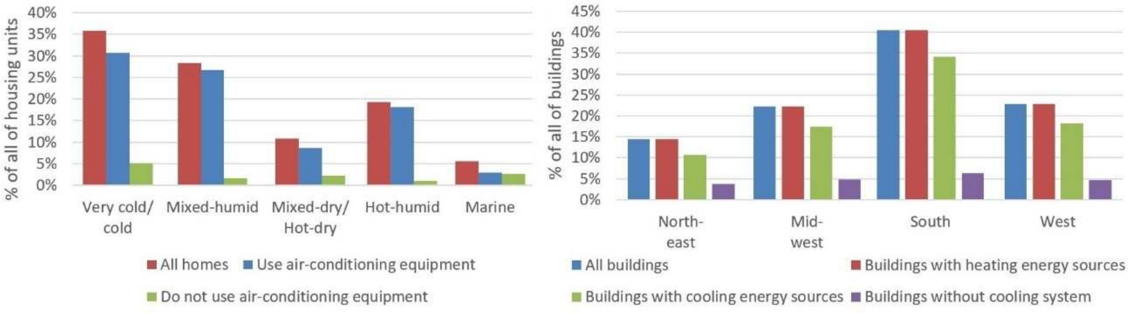


Figure 1 (Left) Percentage of homes and HVAC use in climatic regions of the United States, (Right) Percentage of buildings with energy sources use in regions of the United

States (Source: U.S. Energy Information Administration, Residential Energy Consumption Surveys) [4].

Various techniques have been implemented to improve the building energy efficiency. Traditional air-conditioning methods, such as heat pumps and boilers, are mostly active strategies. However, air conditioning is recognized as a significant factor in global warming and climate change [5]. On the other hand, there is a growing interest in utilizing passive and low-energy systems for cooling buildings, both residential and commercial. Moreover, according to the U.S. Energy Information Administration (EIA), the Commercial Buildings Energy Consumption Survey [6], the country has 5,557 thousand of Commercial buildings. Divided in four census regions, where all the building use heating energy sources, and a high percentage of buildings with cooling energy sources (Figure *2*).

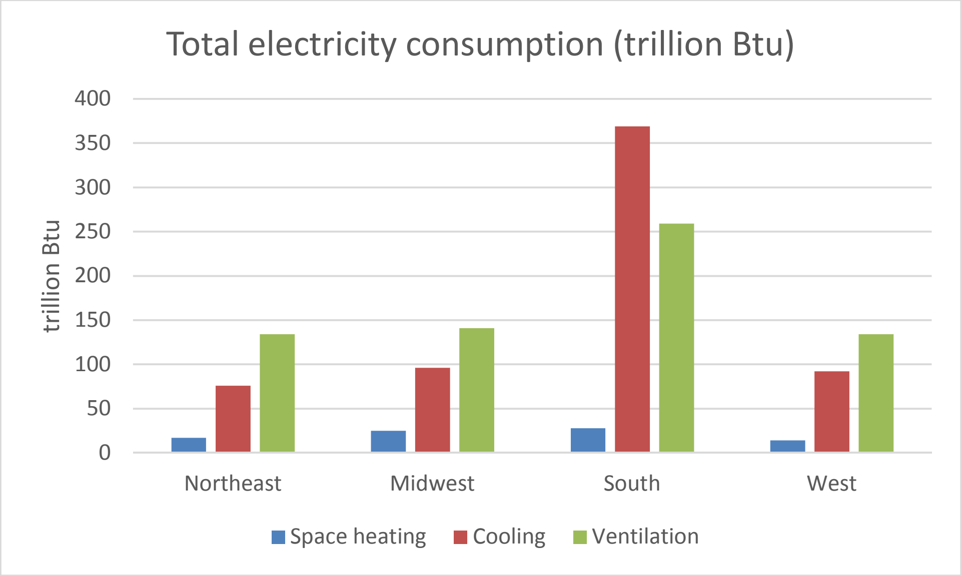


Figure 2 Total electricity consumption in commercial buildings. Energy Information Administration (EIA), the Commercial Buildings Energy Consumption Survey [6]

HVAC are conventional means of creating thermal comfort, however, they are energy intensive and less ecological. Passive cooling can be adopted as a viable alternative, because these technics can remove heat sensibly if the air is cooler or by evaporating water if it is dry [7]. In the search for alternatives, passive downdraught evaporative cooling (PDEC) is proving to be both technically and economically viable in different parts of the world [5]. Following the theoretical and experimental work by Baruch Givoni in Israel, and by Cunningham and Thompson in Arizona, a number of pioneering buildings adopting this innovative technique have emerged around the world [8]. In the last years, the Passive and Hybrid Downdraught Evaporative Cooling (DEC) is a viable alternative to conventional mechanical cooling in buildings. These first-generation buildings demonstrate the technical applicability of Passive and Hybrid DEC as part of a climatically responsive approach to design and to the provision of comfort [8]. Different simplified simulation models of a PDEC have been developed and compared. The results could help designers in choosing amid different calculation models [9].

The downdraught cooling solutions are classified into three types:

(1) The Passive Downdraught Evaporative Cooling (PDEC): when downdraught is achieved through the evaporation of water within an air stream. The passive cooling refers to the exploitation of an ambient heat sink to achieve cooling. The idea is based on the fact that the latent heat of water evaporation is absorbed from the passing hot-dry air stream. The process is an adiabatic humidification process in which part of the sensible heat of the air stream is transferred to latent heat. Therefore the sensible heat of the air stream decreases and its DBT decreases, while on the contrary, its latent heat increases, and as a result, the air supplied is not only cooler, but is also more humid. Due to this, it is used as a passive cooling system or part of a complex cooling system. This system works as a complete passive cooling, because in general, no active parts are added (such as pumps or fans). However, when there is no wind and the downdraught

airflow relies solely on buoyancy forces, this solution is not feasible, and in this case needs to use fans to enhance the air distribution.

(2) The active downdraught cooling (ADC): when the cooling is achieved by using chilled water cooling coils or panels, driving air over evaporative cooling pads directly into the building, which means the strategy relies on mechanical cooling. This technique is an alternative to conventional air conditioning that can contribute to reduce the energy consumption because only the mechanical system needed for the air-cooling is responsible of this energy consumption.

(3) Hybrid downdraught cooling (HDC): when it combines both ‘passive’ and ‘active’ downdraught cooling techniques. This technique is an alternative to conventional air conditioning that can contribute to reduce the energy consumption because only needs alternatively, the mechanical system needed for the air cooling, or the fans required for the air circulation and distribution.

These techniques have a good potential to provide an alternative to conventional air conditioning systems offering comparable comfort levels with reduced energy consumption and therefore reduced greenhouse gas emissions. Evaporative cooling techniques have been proved feasible both from economic and technical stand points through numerous studies, nevertheless their efficiency can dramatically be reduced in the case of hot humid climates [10]. The systems use evaporative cooling in hot and dry conditions and chilled water cooling coils in warm and humid conditions [11].

In the case of the U.S., it is possible to derive in which parts of the country these techniques can be applied, and the potential of the application, taking into account the climatic data of the meteorological databases known in this country. The high potential for application of these techniques in buildings could reduce their energy impact substantially.

In this article the applicability of the above-mentioned innovative solutions is going to be studied within the United States of America.

2. General climate classification in U.S.

The United States is the world's fourth largest nation by total area, with its large size and geographic variety, it includes most climate types. The specific climatology of each county is shown in Figure 3, according to the Köppen climate classification, Table *1*, [12].

Table 1 Köppen-Geiger classes included in the U.S.

Climate class	Climate name	Climate class	Climate name
Af	Tropical rainforest climate	Cwa	Monsoon-influenced humid subtropical climate
Am	Tropical monsoon climate	Cwb	Subtropical highland climate or Monsoon-influenced temperate oceanic climate
Aw	Tropical wet and dry	Dfa	Warm/Humid continental climate
Bwh	Warm desert climate	Dfb	Temperate/Humid continental climate
BSh	Warm semi-arid climate	Dfc	Cool continental climate / Subarctic climate
BWk	Cold desert climate	Dwa	Warm/Humid continental climate
BSk	Cold semi-arid climate	Dwb	Temperate/Humid continental climate
Csa	Warm Mediterranean climate	Dwc	Cool continental climate / Subarctic climate
Csb	Temperate Mediterranean climate	Dsa	Warm/Mediterranean continental climate
Cfa	Warm oceanic climate/ Humid subtropical climate	Dsb	Temperate /Mediterranean continental climate
Cfb	Temperate oceanic climate	Dsc	Mediterranean-influenced subarctic climate
Cfc	Subpolar oceanic climate	ET	Tundra climate

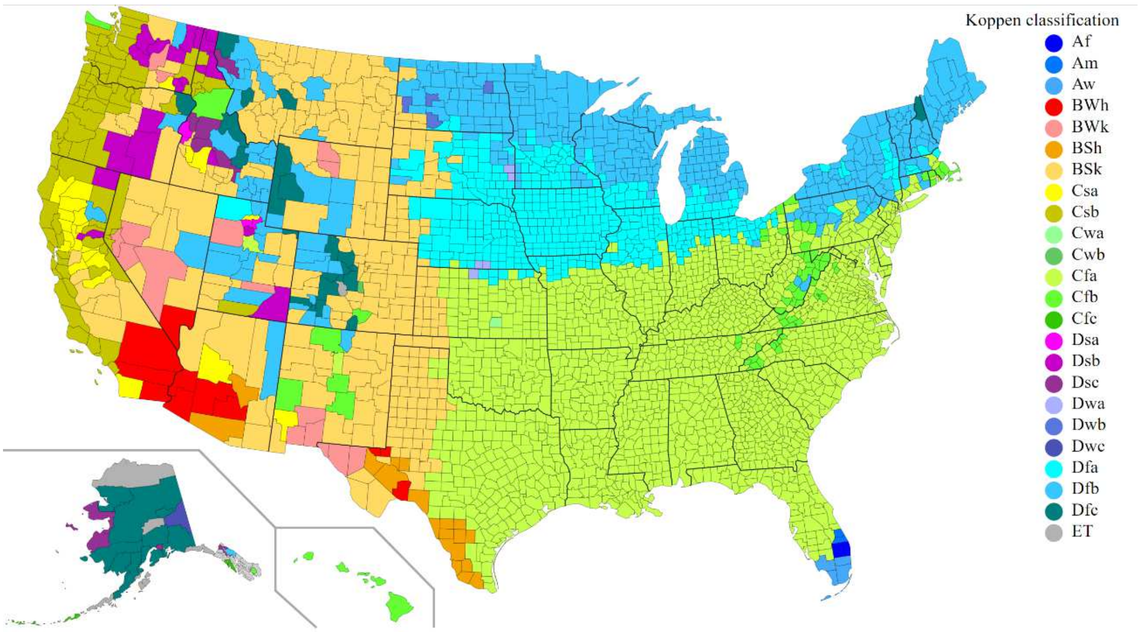


Figure 3 Climate regions of the U.S. according to the Köppen climate classification.

Approximately, to the east of the 100th meridian, the climate ranges from humid continental in the north to humid subtropical in the south. The Great Plains west of the 100th meridian is semi-arid. Much of the Western mountains have an alpine climate. The climate is arid in the Great Basin, desert in the Southwest, Mediterranean in coastal California, and oceanic in coastal Oregon and Washington and southern Alaska. Most of Alaska is subarctic or polar. Hawaii and the southern tip of Florida are tropical, as being the populated territories in the Caribbean and the Pacific.

This study will identify the different zones of applicability of evaporative cooling in maps of the U.S., without taking into account the proposed climatic zones, but will use climatological data to develop maps at the same high-resolution level (county) as the Building America program map. The Building America climatological map will be used for validation purposes only and to verify the consistency of the results later on. However, this paper, uses the same sub-division level: the county. The county is an administrative or political subdivision of a state and it is a region having specific boundaries and usually some level of governmental authority. It is analyzed a total of 3,142 counties and county-equivalents in the United States. According to this subdivision, each administrative unit has been represented by the climate of a location for which the applicability assessment procedure was illustrated. Following this, four case study buildings using PDEC were identified in the states of Arizona, Utah and California, for which a post-occupancy study was previously undertaken [13] and further detail applicability analysis illustrated.

3. Map of downdraught cooling

The following applicability maps are conceived to give architects and engineers an overview of the appropriate downdraught cooling strategies during the initial conceptual stage of the design.

The methodology followed has been described previously in chapter 6 of a manual on downdraught cooling [11]. Following that publication [11], more detailed applicability studies were developed for Europe and China, but never for the U.S.. Other authors purpose to assess the applicability of an indirect evaporative passive cooling system in houses across the Brazilian territory [14] or in India [15].

Analysis of conditions at a given location must be based on long-term climatic averages, such as the Typical Meteorological Year (TMY) [16]. In this study the synthetic climatic data obtained from National Solar Radiation Data Base (NSRDB) archives has been used. As they are based on more recent and accurate data, these new data sets are named TMY3 [17]. The TMY3 data set contains data for 1020 locations, representative of 761 counties. The source data is available for download from the National Renewable Energy Laboratory [17]. This data set is available for download in EnergyPlus weather format and include hourly values of solar radiation and meteorological variables for a 1-year period. Their intended use is for computer simulations of solar energy and building systems in order to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories. The WBT was calculated based on the Stull formula, an equation for wet-bulb temperature as a function of air temperature and relative humidity [18].

These data were required in order to analyse and evaluate the viability of evaporative cooling at the early design stage. However, a limitation encountered was related to the lack of detailed data to increase the resolution of the map. In fact, the meteorological data for each county can only be applied within a radius of 50 km from the nearest weather stations [19]. For this reason, it was necessary to interpolate parameters between stations, in the development of the maps, the extrapolation technique was used from Sanchez et al. [20]. In this study, a radius of 200 km and a maximum of 6 stations was used to generate interpolated data, with the exception of 36 counties in which it was necessary to use a greater radius. In the worst case the radio was 270 km. Sanchez’s method is based on a 3-D inverse distance model (Shepard’s gravity interpolation). The height of the surface above sea level at this point is a data from the NASA and the CGIAR Consortium for Spatial Information database. The point analysed for the purpose of interpolation was the main county seat. This is an administrative centre, seat of government, or capital city of a county or civil parish. The meteorological data derived was used to analyse the indices characterizing the potential for applicability of passive downdraught evaporative cooling.

In this paper, the approach described in the design sourcebook, ‘The Architecture & Engineering of Downdraught Cooling’ [11], is used as the basis to analyse climate data and the applicability of evaporative cooling in the U.S.. A detailed explanation of the evaporative cooling process is also described in Alvarez [21]. Frequency hours of difference between outdoor dry bulb temperature (DBT) with outdoor wet bulb temperature (WBT), and design indoor DBT with outdoor WBT from

June to September were calculated for each county of the U.S.. The design indoor DBT was assumed to be 26ºC, The set point temperature was set to 26°C, according to similar analyses reported in literature in Mediterranean area [22], China [23], India [14]. Other studies use different values, in any case a temperature should be used according to the comfort of the occupants. According to adaptive comfort theories, which are even more applicable when using passive air conditioning systems, the comfortable temperature range for summer can be considered between 25 and 28ºC [24–27]. The minimum value of the evaporative cooling outlet temperature would be (in a theoretical optimum situation) equal to the WBT.

The two indexes, DBT−WBT (Figure 4) and 26ºC−WBT, indicate the potential of evaporative cooling and the possibility of using evaporative cooling to reduce the cooling demand and they are used as indicators of the cooling potential of the evaporative system. Both indices are calculated from June to September, the values represented are average values in the 2928 hours of the analysis period (TMY). In order to absorb heat from the space being cooled, the wet bulb temperature must be substantially low. In fact, simply noting a large wet bulb temperature depression is not in itself an indication that conditions at a given place and time favour evaporative cooling for cooling proposes: the wet bulb temperature must be below 24ºC, and this is reflected in the 26ºC – WBT criteria.

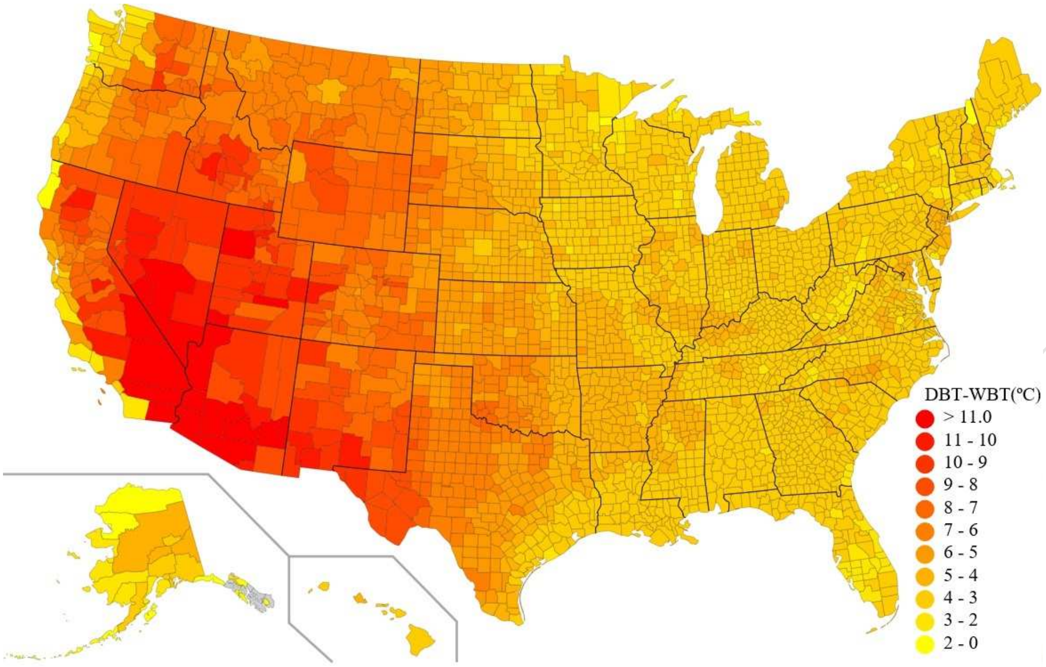


Figure 4 Difference between the outdoor DBT and outdoor WBT during summer period.

For consistency with the Chinese and European maps [28,29], five applicability zones have been defined (Figure 5). Places where the depression of DBT and WBT is higher is indicated as zone 1 (≥ 9.5ºC) and it is where the potential of Passive and Hybrid DEC systems to cool the air is more applicable. The subsequent zones are defined as follows: zone 2 (9.4ºC – 7.2ºC), zone 3 (7.1ºC – 5.0ºC), zone 4 (4.9ºC-2.6 ºC), and zone 5 (< 2.6ºC). The places where the depression of DBT and WBT is lower, it is where ADC is more applicable.

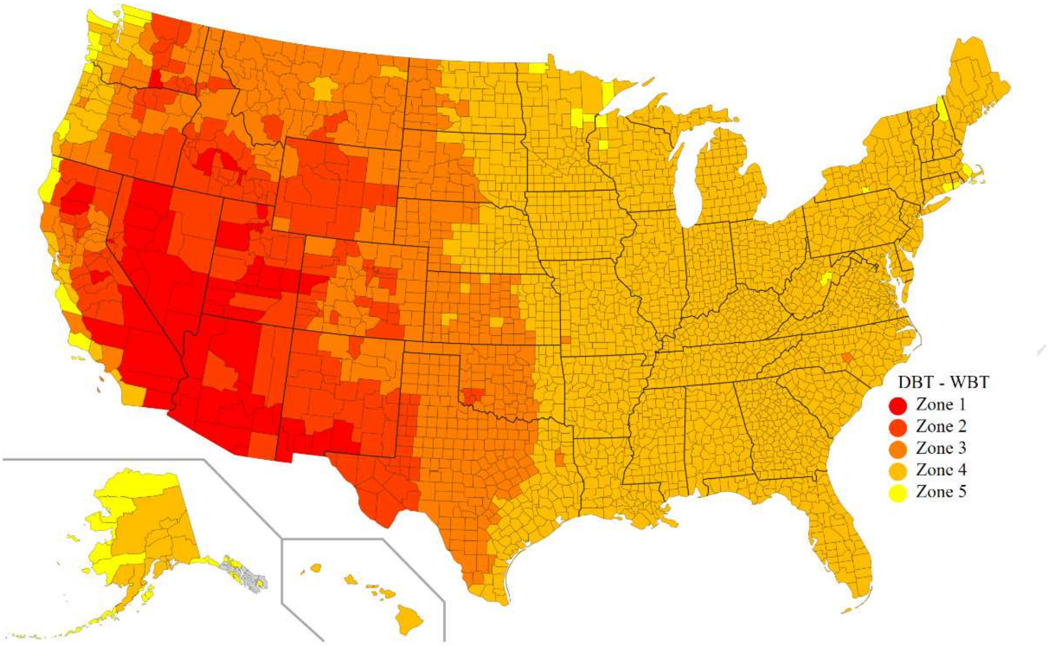


Figure 5 Zones of applicability based on differences between the outdoor DBT and outdoor WBT during summer period.

Figure 6 shows the potential of evaporative cooling to reduce cooling demand in the building with a PDEC system that theoretically could supply the air in wet bulb conditions. Also a map with five zones of applicability has been drawn. At the high level, zone 1 (>10.2ºC), where the reduction in cooling demand would be higher using PDEC, in the middle is represented by zone 2 (10.1ºC – 7.9ºC) and zone 3 (7.8ºC – 5.5ºC), a low level is defined by zone 4 (5.4ºC-3.1ºC), and the rest is defined by zone 5 (<3.1ºC), representing a lower level of applicability where the PDEC system cannot effectively cool the building due to the temperature difference 26ºC−WBT is small, but where ADC can be an effective strategy.

These maps of DBT−WBT and 26ºC–WBT offer an easy way to understand the overall climate of the U.S. and its relation to the applicability of passive and active downdraught cooling. The resolution of these sets of maps could be higher in order to obtain the applicability in a determined location.

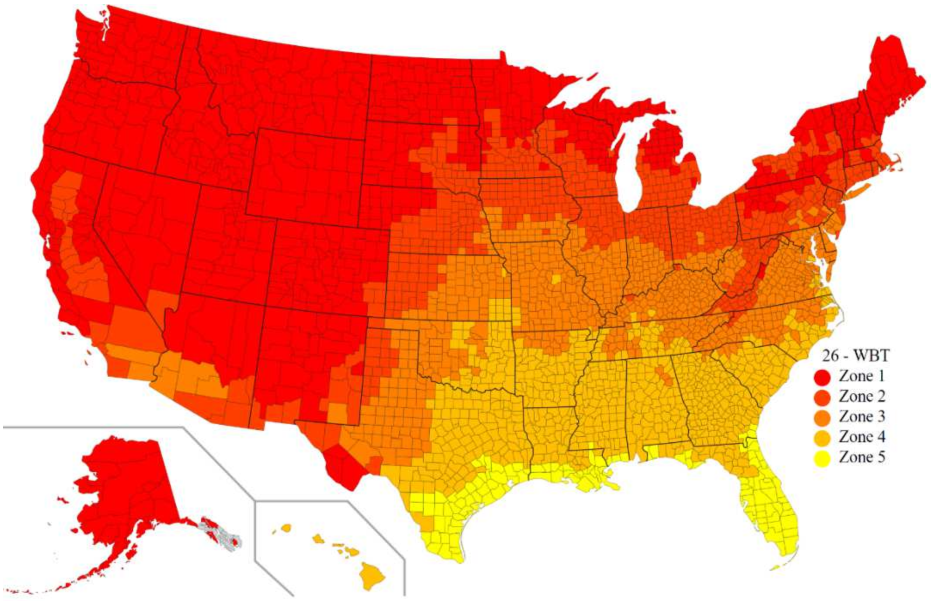


Figure 6 Zones of applicability based on differences between indoor design temperatures and outdoor wet bulb temperatures.

4. Map of intervention categories

The applicability in terms of priority of intervention in the case of the U.S. can be defined by comparing the maps in Figure 5 and Figure 6. The comparative analysis of these maps is shown in Table 2. The potential for cooling varies among different regions and over time at a specific location. These variations must be assessed in order to decide upon the feasibility of applying evaporative cooling in a proposed building projects. For example, a location in the zone 1 in terms of climatic potential (DBT−WBT), and also in zone 1 in terms of potential of cooling (26ºC−WBT) could be considered a location with the highest potential for application. Table 2 shows a classification of locations as a function of their potential for application in four categories (very high, high, medium, low and very low), depending on the cross-potential of air cooling through evaporative systems and the potential for the cooled air to reduce the cooling energy demand of the building. In Table 2, the potential for cooling the air (DBT−WBT) is prioritized, because it is possible to achieve greater cooling by increasing the air flow if the second potential (26ºC−WBT) is not sufficiently high. Figure 7 shows the levels of priority of intervention in the U.S. based on Table 2. The cooling demand of each city needs to be considered, thus the climate where downdraught cooling applications are feasible generally should be warm and with a moderate-to-high demand of cooling during the summer. These conditions appear in the U.S. in many counties in the middle and south-west.

Table 2 Categories of priority of intervention

		26ºC-WBT				
		Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
DBT-WBT	Zone 1	Very high	Very high	Very high	High	-
	Zone 2	High	High	Medium	Medium	-
	Zone 3	Medium	Low	Low	Low	-
	Zone 4	Very low	Very low	Very low	Very low	-
	Zone 5	-	-	-	-	-

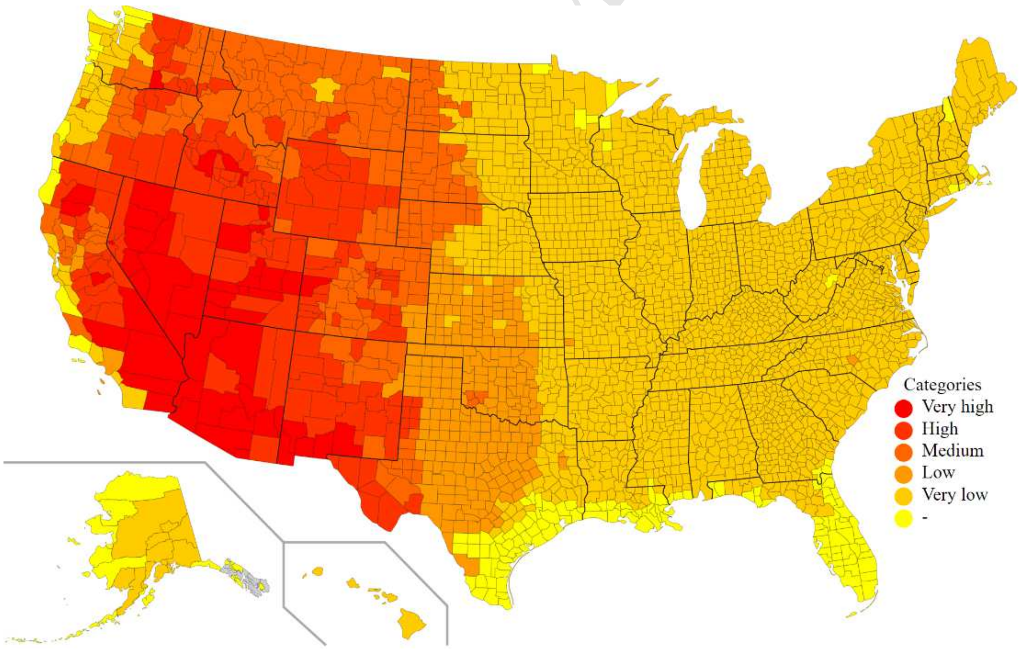


Figure 7 Levels of priority of intervention in the U.S.

5. Map of cooling degree days and its relation to downdraught cooling design strategies

Cooling degree days represent the number of degrees and days where the outside temperature is higher than the base temperature. Cooling degree days can be used to help assess or compare different potential sites for development of cooling strategies. They can also be used as a way of normalising weather between different sites, allowing a comparison of the performance of different buildings. The use of degree days should be treated with caution as part of a broader process of analysis, providing a general indicator for order of magnitude assessments rather than for accurate, detailed comparisons. In the United States, a simplified method is used to calculate both heating and cooling degree days [30]. The mean (high temperature plus low temperature divided by two) daily temperature in Celsius and a nominal temperature of 18.3°C (65°F) are used. If the mean daily temperature is 18.3°C, no degree days are counted. If the mean daily temperature is below 18.3°C, the mean degrees below 18.3°C are counted as the heating degree day. If the mean daily temperature is above 18.3°C, the mean degrees above 18.3°C are counted as the cooling degree day. In Figure 8 the number of cooling degree days is shown. According to Figure 7 and Figure 8, the hot and dry climate regions show good potential for the use of PDEC, during the summer period. This strategy should be integrated with sun shading, high thermal mass with night ventilation and natural ventilation. Conventional air conditioning would only be required in summer under extreme hot conditions for a short period of time. However, if the neutral comfort temperature is calculated by an adaptive model [24–27], Passive and Hybrid DEC, together with other applicable passive strategies, will obtain thermal comfort on a longer period of time and possibly 100% of the occupied.

In hot and moderately humid climates, in some periods (the hottest or high humidity days) the cooling produced by PDEC may not be sufficient to cover 100% of the cooling requirements. In these circumstances, a back-up system in conjunction with PDEC, a hybrid downdraught cooling system (HDC), has to be operated to meet the cooling load.

For the hot and high humid climates, PDEC techniques cannot be operated at all, because the outdoor relative humidity is too high. However, the ADC strategy with cooling coils or panels can be proposed in this climate to cover the cooling requirements, and could save 25–35% of the electrical energy required in the building by relying on buoyancy-driven airflow [28].

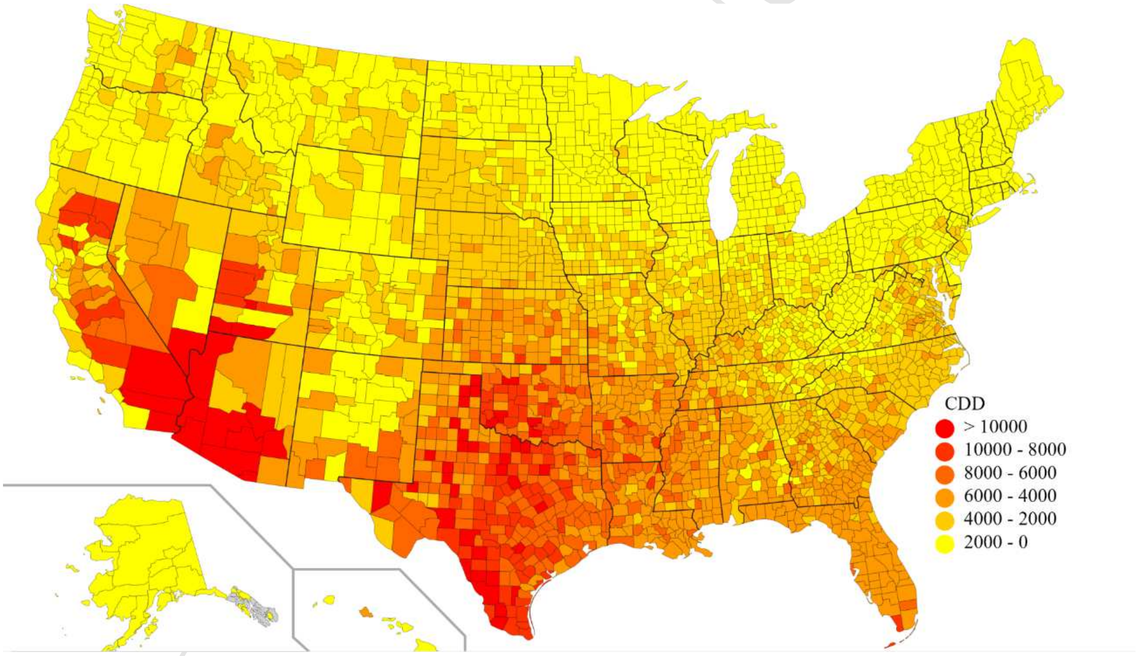


Figure 8 Cooling degree days in the summer.

The applicability map has been obtained by overlapping the categories of intervention and the cooling degree days maps following the rules given in Table 3. It aims to give a useful, simple and accurate method for designers, engineers and architects in order to assess the potential application of downdraught cooling systems in the U.S.

shows that a high number of counties in the west of the 100th meridian belong to the high or very high classes of applicability.

Table 3 Downdraught cooling applicability.

		CDD					
		>10000	8000-10000	6000-8000	4000-6000	2000-4000	<2000
Level of intervention	VH	VH	VH	VH	H	M	M
	H	VH	VH	H	H	M	L
	M	VH	H	H	M	M	L
	L	M	M	M	M	L	L
	VL	L	L	VL	VL	VL	VL

*VL – very low, L – low, M –medium, H – high, VH – very high applicability

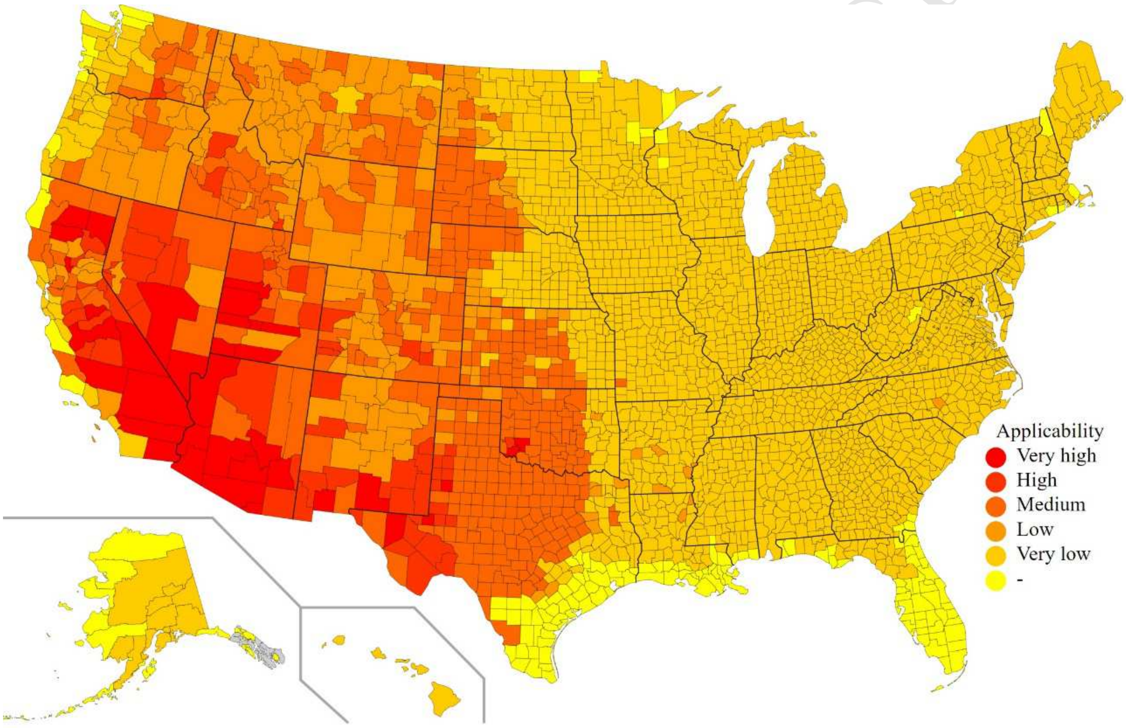


Figure 9 Downdraught cooling applicability maps.

In Table 4 shows the number of counties in each climatic zone, according to the Köppen classification, and the level of applicability found in each climate zone. Based on the five main climate groups in the Köppen climate classification, the wider applicability is presented in arid climate (B), moderate in temperate climate, low in continental climate (D) and no applicability or very low in tropical climate (A) and polar climate (E). Note that in Table *4* is based on counties, which have unequal sizes, as shown on the map, high applicability counties are larger in size.

Table 4 Number of counties classified by level of intervention in each Köppen climate

	Level of intervention							Level of intervention					
Köppen classification	VH	H	M	L	VL	-	Köppen classification	VH	H	M	L	VL	-
Af	0	0	0	0	0	1	Cwa	0	0	1	0	0	0
Am	0	0	0	0	0	2	Cwb	0	0	1	0	0	0
Aw	0	0	0	0	0	4	Dsa	0	0	2	2	0	0
BWh	9	2	0	0	0	0	Dsb	0	1	7	11	1	0
BWk	4	5	6	1	0	0	Dsc	0	1	3	1	1	3
BSh	2	2	5	6	1	2	Dwa	0	0	0	0	5	0
BSk	11	36	143	91	3	0	Dwb	0	0	0	3	1	0
Csa	3	6	10	3	1	0	Dwc	0	0	0	0	1	0
Csb	3	5	11	21	34	12	Dfa	0	0	15	12	410	0
Cfa	2	1	171	27	1414	101	Dfb	2	4	20	33	311	9
Cfb	0	0	1	5	62	7	Dfc	0	1	7	14	7	4
Cfc	0	0	0	0	0	2	ET	0	0	0	1	1	4

6. Applicability analysis in real buildings

In order to validate the mapping approach and verify the applicability predictions, a more detailed analysis of the climatic applicability of downdraught cooling in relation to the performance of buildings that have implemented this type of system in different climatic conditions was undertaken. Four pairs of buildings and counties were selected: Sonoma (building 1) and Stanford (building 2) in the state of California, Washington (building 3) in Utah and Maricopa (building 4) in Arizona. The buildings represent the different conditions of three distinct climates.

California is defined by DOE-BAP as a Hot-Dry region, however, it benefits from a Mediterranean climate in the greater San Francisco area, characterized by mild wet winters and dry sunny summers (mean max temperatures of 28ºC and afternoon RH of 35%). This is experienced in buildings 1 and 2: Kenilworth High School, in

Petaluma, in the county of Sonoma, and the Global Ecology Research Centre, Stanford, in the county of Santa Clara. Petaluma enjoys a mild Mediterranean climate. The dry summer is characterized by typically warm days and cool nights. Standford is warm (but not hot) with dry summers. According to the Köppen Climate Classification system, Stanford has a warm-summer Mediterranean climate (Csb) [12].

Utah is defined by DOE-BAP as a Cold region, the climate of South Utah is hot and dry in summer (with mean max temperatures of 32ºC and RH of 20%) but the microclimate of the Zion National Park (building 3: Visitor Centre, Zion National Park) is influenced by the canyon system, which provides greater annual rainfall and smaller diurnal swings.

Maricopa county in Arizona is defined by DOE-BAP as a Hot-Humid region, but in the more extreme climate of south Arizona, it is characterized by mild winters and very hot and dry summers (mean max temperatures of 41ºC in August and afternoon RH of 20%). This climate is experienced in building 4, the Sandra Day O’Connor Federal Courthouse, in Phoenix.

According to the classification proposed by Ford [11], these buildings (Table 5, Figure 10) fall under the following typologies:

(a) downdraught cooling (DC) system in large atrium for building 4,

(b) DC tower attached to adjacent spaces for buildings 1, 2 and 3.

The description of these four buildings and an extensive study of their post-occupancy evaluation was published in 2012, the surveys and the questionnaire mention the occupant satisfaction [8]. This study revealed that PDEC systems in increasing occupants’ satisfaction with their thermal environment. The study evaluated the occupants’ satisfaction for the four buildings respect to temperature and air during the summer and winter, lighting, noise, comfort, design, needs, health, image to visitors and productivity. The best solutions were in Global Ecology Research Centre (Stanford) and Visitor Centre (Springdale) where the post-occupancy evaluation (POE) is positive in overall aspect. On the contrary, the life-style and cultural expectation affect the POE in the Federal Courthouse (Phoenix), because air-conditioned courtrooms and offices are kept at a considerably lower temperature (21ºC-23ºC).

The POE it is an emerging research topic, in [31], the authors conducted a comprehensive and critical review and suggest five directions for future POE development and applications.

Table 5 Information about the building locations and climatic characteristics.

Buildings		**1**	**2**	**3**	**4**
		Kenilworth High School	**Global Ecology Research Centre**	**Visitor Centre, Zion National Park**	**Sandra Day O'Connor Federal Courthouse**
Location	City	Petaluma	Stanford	Springdale	Phoenix
	County	Sonoma	Santa Clara	Washington	Maricopa
	State	California	California	Utah	Arizona
	FIPS	6097	6085	49053	4013
	Latitude:	38.52	37.62	37.08	33.45
	Altitude:	-122.82	-122.40	-113.60	-111.98
	Weather file:	Santa Rosa, CA, USA (TMY3)	San Francisco Intl. Ap., CA, USA (TMY3)	Saint George, UT, USA (TMY3)	Phoenix Sky Harbour Intl. Ap., AZ, USA (TMY3)
SUMMER June – September	Avg. DBT (ºC)	18.09	18.71	29.42	33.07
	Avg. DPT (ºC)	11.47	11.92	4.05	9.47
	Avg. RH (%)	70	67	22	26.5
	Avg. WBT (ºC)	14.00	14.48	15.46	19.15
	DBT – WBT (ºC)	4.09	4.23	13.95	13.98
	26-WBT (ºC)	12.06	11.52	10.54	6.86
	Nº Hours where DBT>25º	478	273	2200	2713
	CDH (degree-hour)	1611	445	13586	21268
	Köppen climates [32]	Csb Warm-summer Mediterranean climate	Csb Warm-summer Mediterranean climate	BSk Cold semi-arid climate	BWh Hot desert climate
	Categories of priority of intervention	Very low	Very low	Very high	Very high
	Downdraught cooling applicability	Very low	Very low	Very high	Very high

1.Kenilworth High School, Petaluma, CA.

2.Global Ecology Research Centre, Stanford, CA.

3.Visitor Centre, Zion National Park, UT.

4.Sandra Day O'Connor Federal Courthouse, Phoenix, AZ.

Figure 10 Building in the U.S. with downdraught cooling systems.

Regarding the systems through which PDEC is provided, buildings 2 and 4 use water misting devices while buildings 1 and 3 employ wetted cellulose mats. Both devices provide a source of direct evaporative cooling but the main difference consists in the former injecting nebulized water directly into the air stream, whereas the latter uses a cellulose porous media to absorb and then release the water.

The relationship between the temperature of the air and its moisture content is presented graphically in the psychrometric chart. A typical psychrometric chart can be considered as shown in Figures 11, 12, 13 and 14, which plot the bioclimatic strategies which are climatically applicable in a building. In these figures, the humidity ratio is shown as the ordinate versus dry bulb temperature as the abscissa, both on linear scales. The humidity ratio, also referred to as the moisture content, is expressed in International System of Units (SI) as grams of water per kilogram of dry air, and dry bulb temperature in degrees Centigrade.

The curved lines on the chart are lines of equal relative humidity, and the diagonal ones are lines of constant wet bulb temperature.

Air cannot be cooled by evaporation to a temperature that is lower than its wet bulb temperature. In practice, even this theoretical limit is rarely attained, and the output of most evaporative coolers is at least 2°C warmer than the ambient wet bulb. This implies that even in very dry conditions, where evaporation can cool the air substantially, extremely high ambient temperatures may result in wet bulb temperatures that are theoretically too high for human thermal comfort but could still be perceived as comfortable compared to the dry bulb.

Building bioclimatic charts (BBCCs) [33] were used to assess evaporative cooling design strategy and the hourly values for June to September are plotted along with the direct evaporative cooling boundary as well as other passive design strategies. According to this analysis, each climatic typology was examined based on the applicable downdraught cooling strategy and the building exemplification.

6.1. Applicability analysis in Warm Summer Mediterranean climate

Building 1: Kenilworth High School

The Mediterranean climate experienced in Petaluma, allows the use of PDEC during the hot and dry periods in the summer in combination with convective cooling by natural ventilation at periods of high humidity. The PDEC strategy is implemented in the design of the Kenilworth High School Building by using a cellulose mat system integrated at the top of the downdraught cooling towers. The environmental design strategies adopted in the school building were mainly focused on energy efficiency but poor design of the airflow patterns in many of the spaces and maintenance difficulties, meant that the PDEC system was not very effective and rarely operational [34]. As shown in Figure 11, the climate of Petaluma has a good potential for evaporative cooling, except for few hours when the temperature and the relative humidity are both very high. From the histograms in Figure 16 and Figure 17, it is apparent that during the summer months (June to September) whilst the wet bulb depression is mostly gravitating in the medium to low priority of intervention zones, with the greatest frequency of hours in the range of 1 to 7°C (78%), the cooling demand reduction potential represented by (26°C – WBT) is comparatively higher with the highest frequency found for 14°C and with values of above 10°C for 73% of the time. This highlights the point that where there is low cooling need as the climate is milder and the cooling degree days are lower, there is also a greater potential for the evaporative cooling to meet most of these needs, given the low values of WBT (Figure 15).

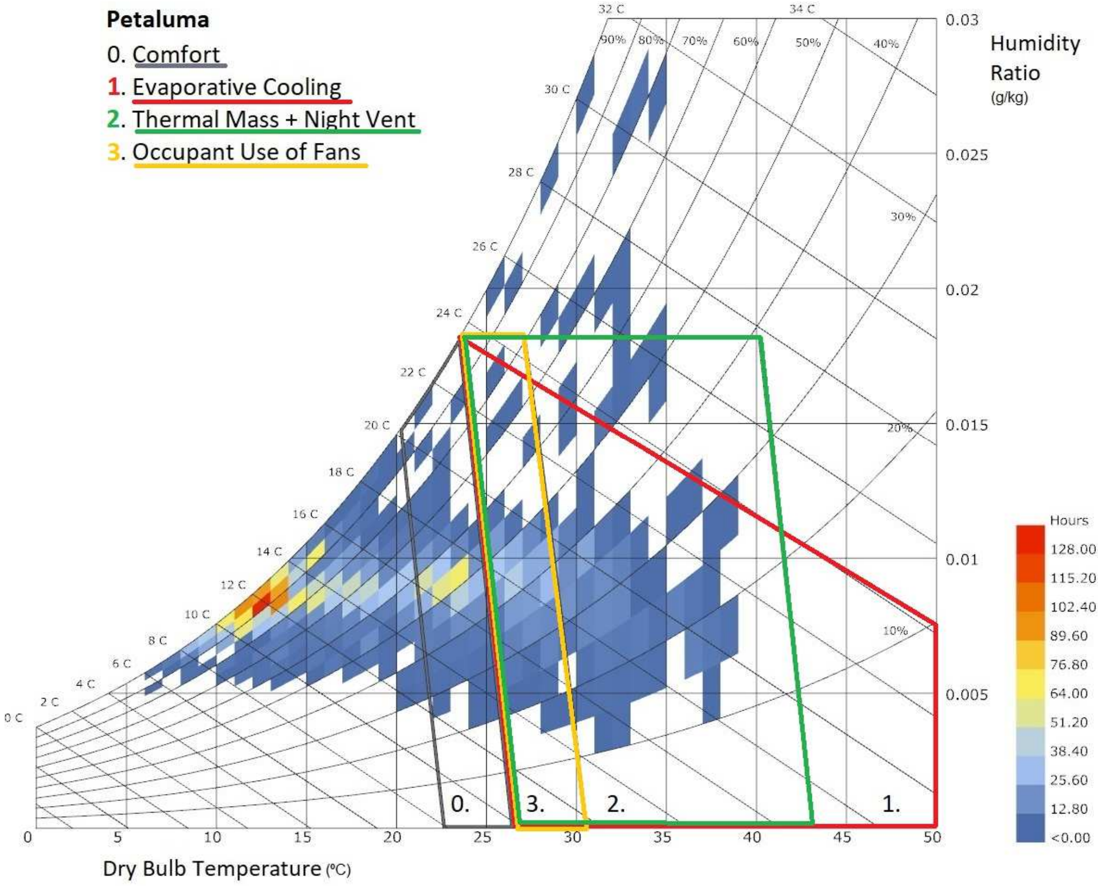


Figure 11 Psychrometric chart for the climate of Santa Rosa, used to characterise conditions for the Kenilworth High School building in Petaluma, CA.

Building 2: Global Ecology Research Centre

The Global Ecology Research Centre in Stanford uses night sky radiant cooling as the main cooling system and, as a secondary system, a PDEC tower employing water misting devices. As shown in the psychrometric chart for San Francisco as representative of Stanford, California (**Error! Reference source not found.**), evaporative cooling is an effective strategy in dealing with the hottest and driest conditions. However, from the frequencies of wet bulb depression and cooling potential indicators (Figure 16 and Figure 17) it is apparent that even if the priority of intervention is low, the cooling potential is high due to WBTs well below the 24ºC threshold (Figure 15). In fact, the frequency of hours when the (DBT-WBT) depression is below 7°C is 85% and the (26°C-WBT) indicator is above 10ºC for 76% of the time. It was found that the PDEC system was only marginally used for the conditioning of the lobby area only during extreme hot weather conditions. This is in line with the output of the mapping which show low strategic opportunity for intervention based on the climate, low cooling needs (see CDD map, Figure 8) but high cooling opportunity during periods of high need.

The level of applicability in this climate is very low, as it was mentioned in the section ‘Map of intervention categories’, the potential for cooling the air (DBT−WBT) is prioritized to assign the global level of applicability, and in this case, it is very low. This coincides with the conclusion that it is can be obtain graphically from the psychrometric diagram [35,36]. Since the meteorological conditions are located outside the preferred zone of action, zone 1, corresponding to evaporative cooling.

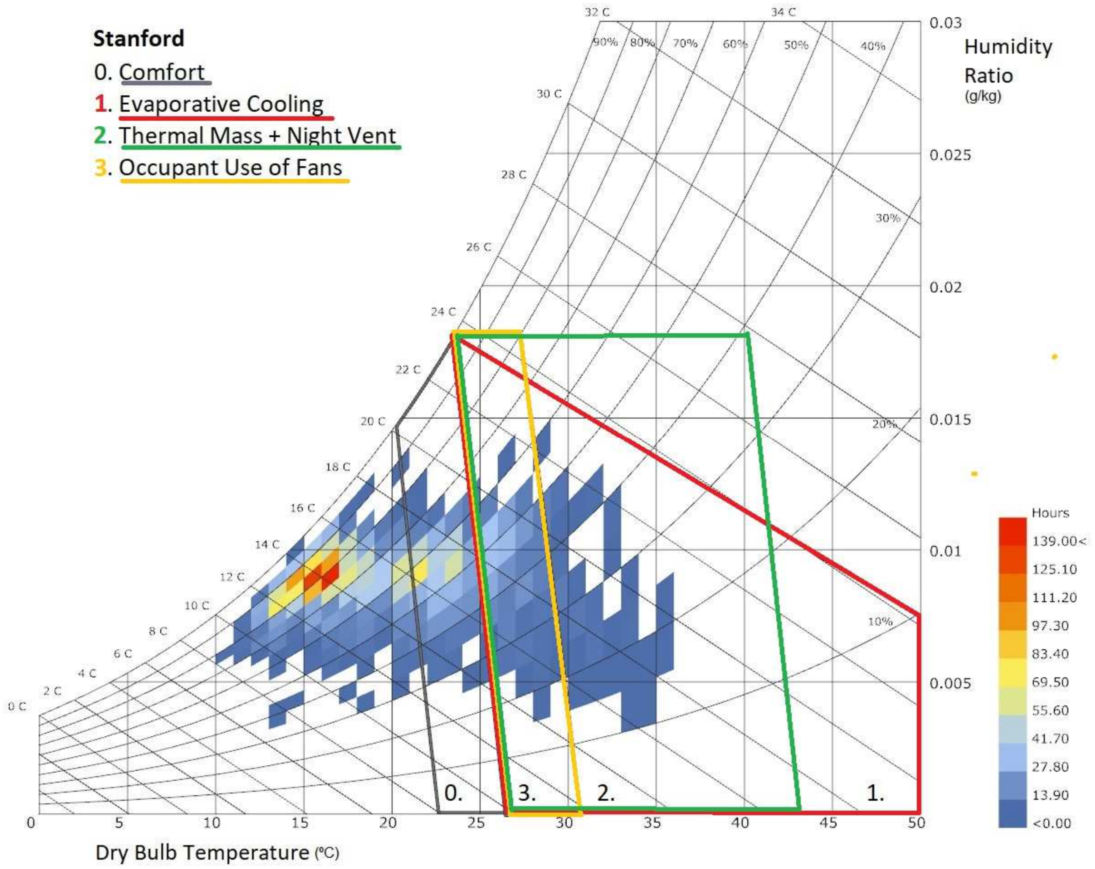


Figure 12 Psychrometric chart for San Francisco weather file characterising the climate of Stanford, CA.

6.2. Applicability analysis in Semi-Arid climate

Building 3: Visitor Centre of Zion National Park

The Visitor Centre of the Zion National Park is located in Springdale in the county of Washington. This location experiences a hot and very dry climate in summer and the building design responded with very low energy and passive strategies for the provision of cooling, using natural ventilation and passive evaporative downdraught cooling. Figure 13 shows the psychrometric chart for the Visitor Centre in Zion National Park, Utah. This indicates the potential to attain comfort by evaporative cooling and the majority of time in summer characterized by very hot and dry conditions. From the mapping exercise this building is located in a zone of high applicability and this is confirmed by both the more detailed climate analysis showing frequencies of (DBT-

WBT) above 7ºC for 5% of time as well as frequencies of (26ºC-WBT) above 10ºC for 50% of the time (Figure 16 and Figure 17). Also, from the post-occupancy study the occupants' feedback was positive and the field visit and building manager's report demonstrated a high level of application of the system which was operational and well-functioning for most of the summer period (Figure 15).

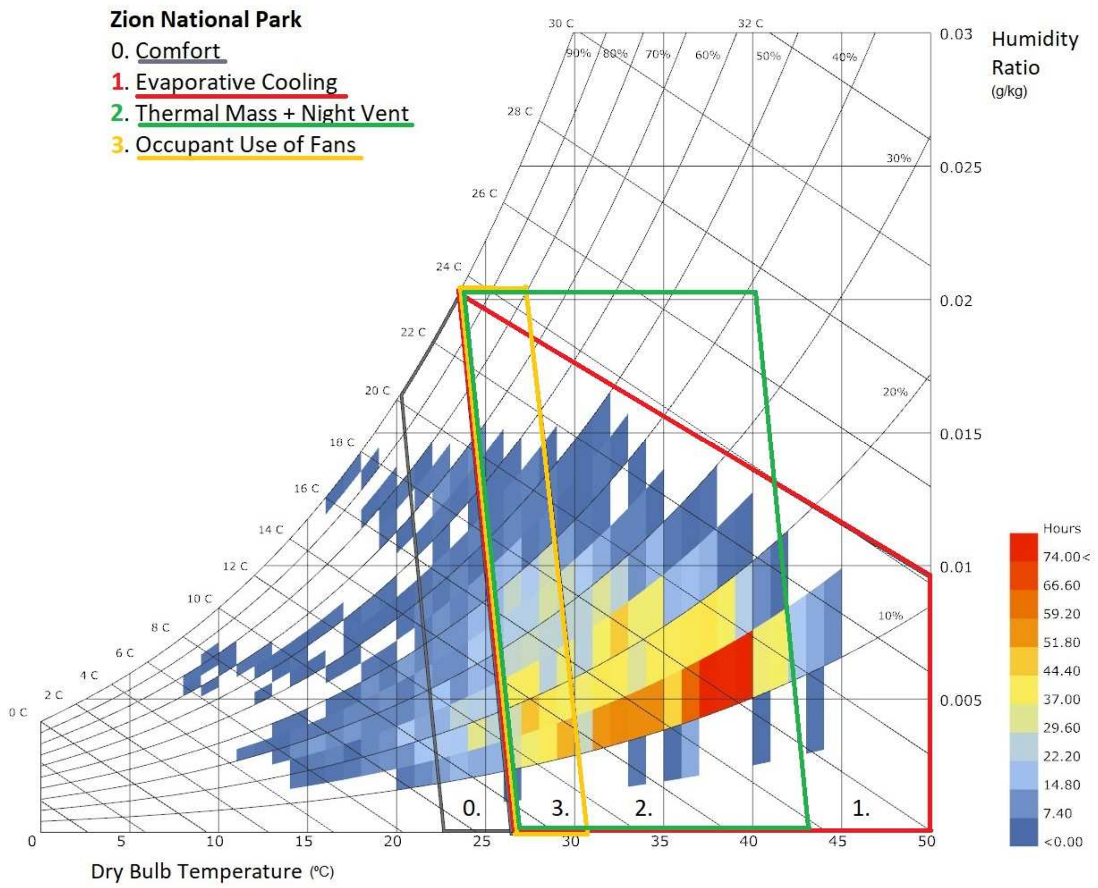


Figure 13 Psychrometric chart in the visitor centre of Zion National Park in Utah.

The level of applicability in this climate is very high, this coincides with the previous and is validated with the conclusion that we can obtain graphically from the psychrometric diagram [35,36], since the meteorological conditions are located inside the preferred zone of action, zone 1, corresponding to evaporative cooling.

6.3. Applicability analysis in Hot and Dry Climate

Building 4: Sandra Day O’Connor Federal Courthouse

The Sandra day O’Connor Federal Courthouse is located in Phoenix where the climate is typically very hot and dry over long summers and a short mild winters. The building’s cooling strategy is composite, with the PDEC system installed in the atrium to provide comfort in the transitional area, and with HVAC systems installed in the office and courtrooms due to a combination of extreme summer temperatures and high specification brief for the typology of spaces. Figure 14 shows the psychrometric chart for the Federal Courthouse in Phoenix, Arizona. As shown in the chart as well as from the frequencies of WBT depression in summer (Figure 16 and Figure 17) there is a great potential for the application of evaporative cooling but clearly this must be aided by additional mitigating strategies to reduce the cooling load. The climatic opportunity for this location is exemplified in the high frequencies of wet bulb depression, with (DBT-WBT) above 7ºC for 5% of the time. However, this is not matched by the cooling potential indicator which showed relatively lower potential due to the high values of the WBT and with frequencies of (26ºC-WBT) above 10ºC for only 13.4% of the summer time (Figure 15).

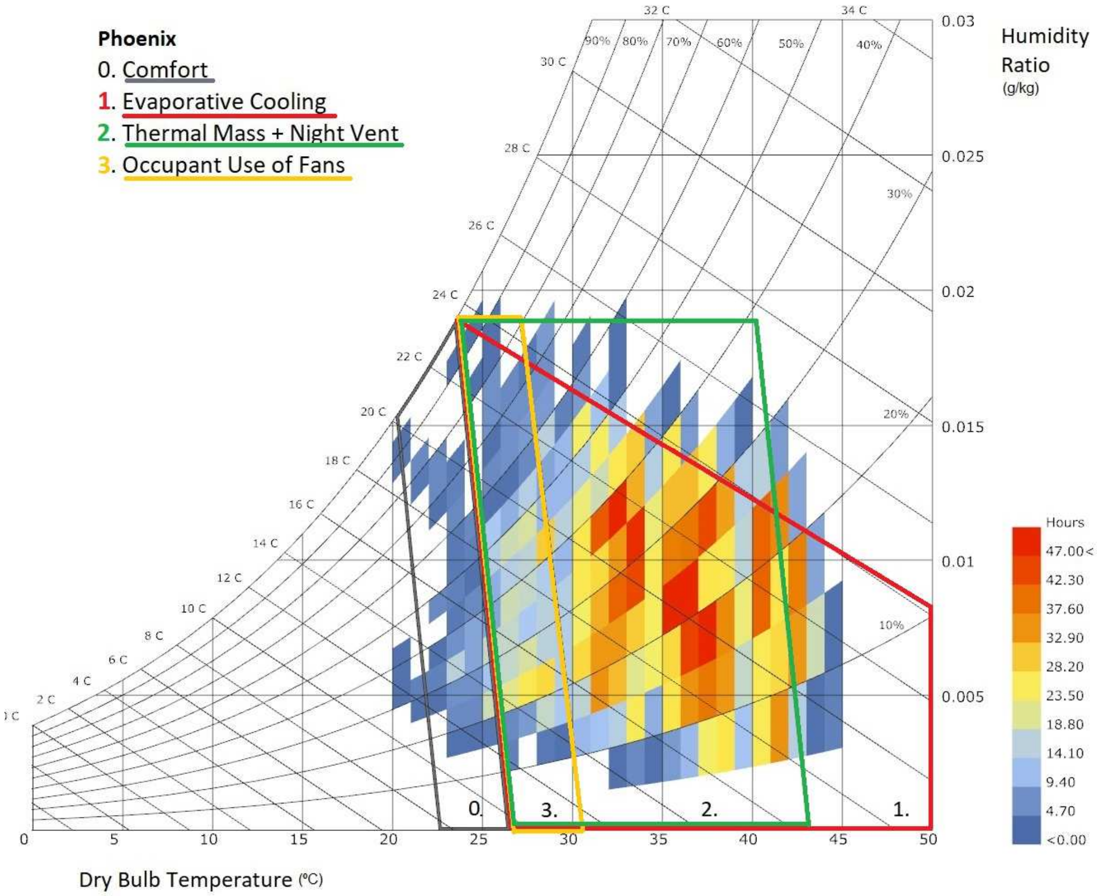


Figure 14 Psychrometric chart in the Federal Courthouse in Phoenix, AZ.

The level of applicability in this climate is very high, this coincides with the previous and is validated with the conclusion that we can obtain graphically from the psychrometric diagram [35,36], since the meteorological conditions are located inside the preferred zone of action, zone 1, corresponding to evaporative cooling.

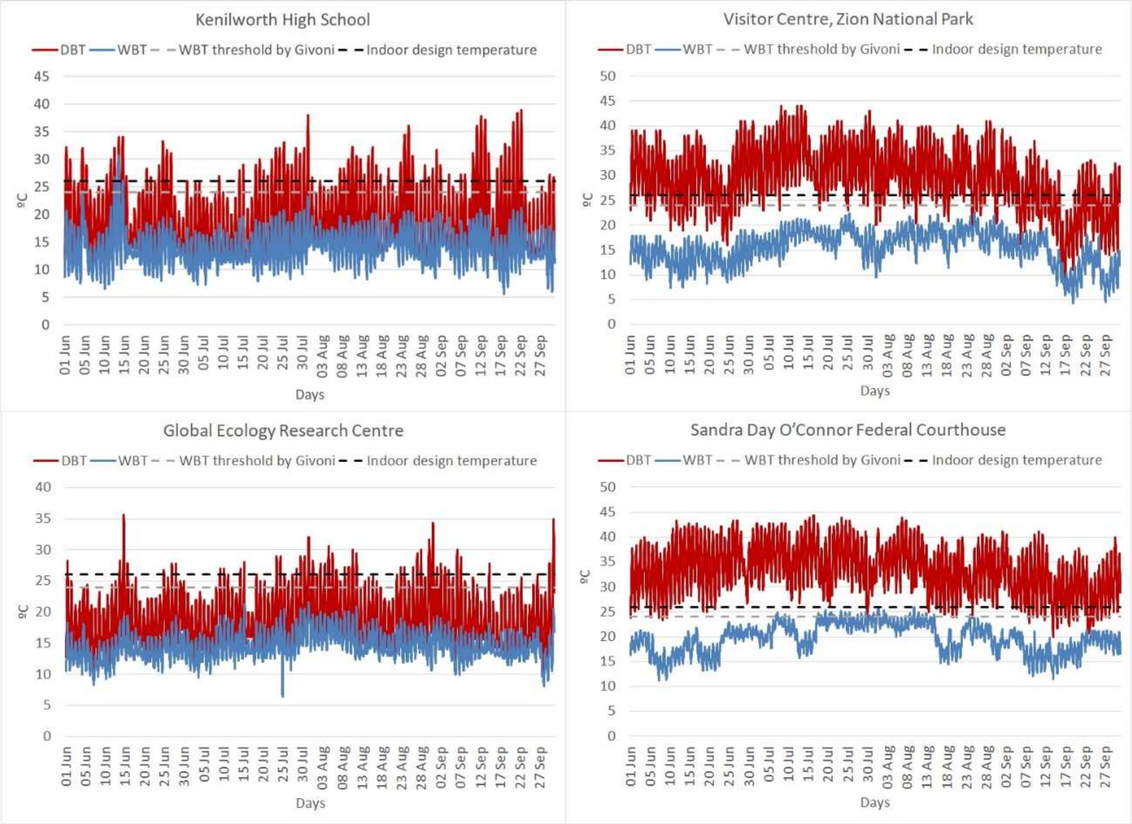
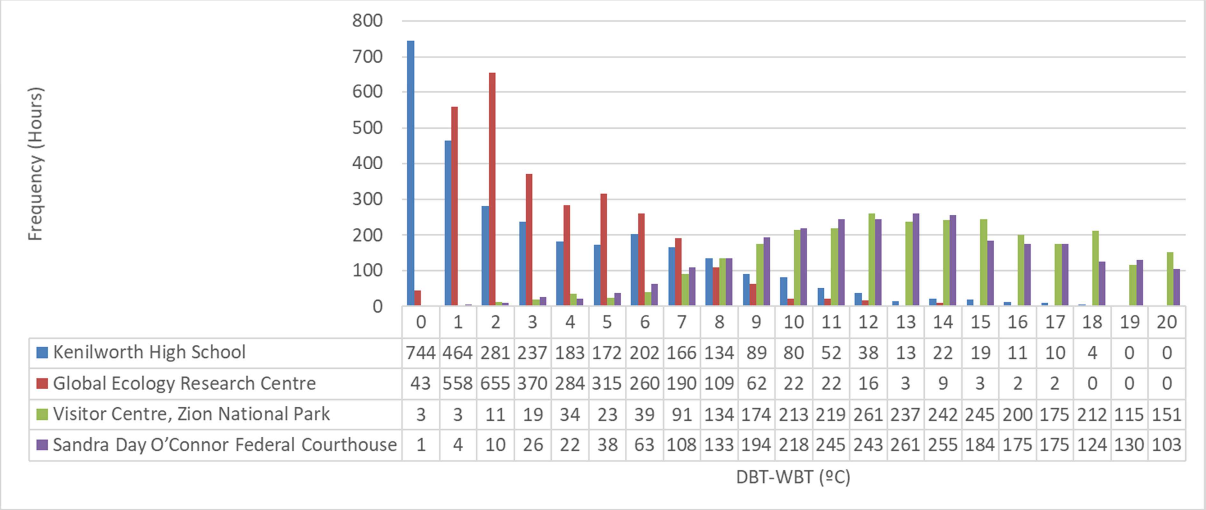
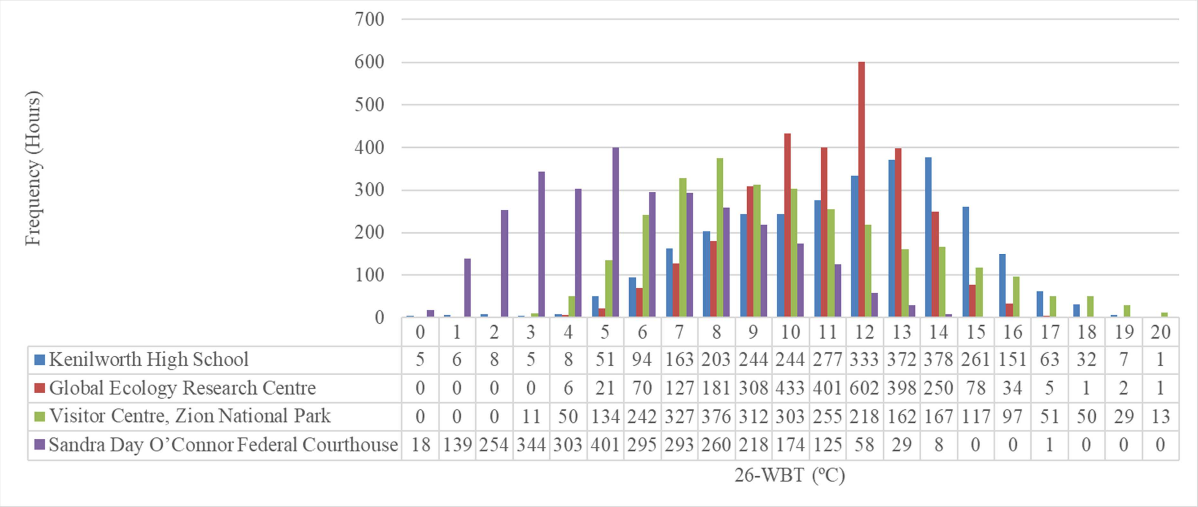


Figure 15 DBT and WBT in the buildings, from June to September.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
🟦 Kenilworth High School	744	464	281	237	183	172	202	166	134	89	80	52	38	13	22	19	11	10	4	0	0
🟥 Global Ecology Research Centre	43	558	655	370	284	315	260	190	109	62	22	22	16	3	9	3	2	2	0	0	0
🟩 Visitor Centre, Zion National Park	3	3	11	19	34	23	39	91	134	174	213	219	261	237	242	245	200	175	212	115	151
🟪 Sandra Day O'Connor Federal Courthouse	1	4	10	26	22	38	63	108	133	194	218	245	243	261	255	184	175	175	124	130	103

Figure 16 Hour frequency of DBT–WBT from June to September.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
🟦 Kenilworth High School	5	6	8	5	8	51	94	163	203	244	244	277	333	372	378	261	151	63	32	7	1
🟥 Global Ecology Research Centre	0	0	0	0	6	21	70	127	181	308	433	401	602	398	250	78	34	5	1	2	1
🟩 Visitor Centre, Zion National Park	0	0	0	11	50	134	242	327	376	312	303	255	218	162	167	117	97	51	50	29	13
🟪 Sandra Day O'Connor Federal Courthouse	18	139	254	344	303	401	295	293	260	218	174	125	58	29	8	0	0	1	0	0	0

Figure 17 Hour frequency of 26ºC–WBT from June to September.

The combined histograms in Figure 16 and Figure 17, demonstrate the potential for climatic applicability of each specific location comparatively. The frequencies of hours above specific ranges for DBT-WBT and 26ºC-WBT have been plotted for the typical cooling season from 1st of June to the end of September. The frequency of WBT depression (DBT-WBT) shows the greater climatic potential and strategic priority for evaporative cooling in Phoenix, Arizona and Springdale, Utah, with frequencies between 133 and 261 hours when the wet bulb depression is quite high, varying between 8 and 20ºC. Whereas the milder and less dry locations of Stanford and Petaluma, present high frequency in the very low band of depressions from 0 to 7ºC. Stanford for example presents a depression of 7ºC for only 190hrs which proportionally represents 8.6% of the time during summer when Passive and Hybrid DEC is potentially more applicable. Looking at the potential for cooling demand reduction and the indicator of 26ºC-WBT (Figure 17), this shows that the highest difference denoting greater cooling effectiveness, is presented by Stanford with 601hrs when the difference 26ºC-WBT is equivalent to 12ºC, representing optimum conditions for applicability for 27% of the time. On the other hand for a very hot and dry climate like that of Phoenix, interestingly, even if the wet bulb depression is high, the cooling potential (26ºC-WBT) is low due to relatively higher WBTs, which are very close to the designated indoor design temperature of 26°C. Therefore, from these observations we can derive that in moderate climates with hot daytime temperatures the 26ºC-WBT index is a more reliable indicator of the climatic opportunity against the theoretical cooling requirement for the location but also that for very hot-dry climates, the DBT-WBT is a still a useful indicator of the climatic opportunity. For the hot-dry climates with high DBT the relatively higher WBTs come closer to the 26°C threshold and therefore show low potential for cooling at 26°C.

For these locations it is suggested that the indoor comfort temperature should be reconsidered and, following the adaptive comfort theory, it should be chosen as the upper limit of the comfort band for each climatic profile (i.e. often greater than 26°C) in order to maximise the evaporative cooling potential given by the local climate. Also, greater accuracy could be obtained by creating maps that can isolate daytime hours from night time hours, in order to identify the cooling opportunity during times of greater need. Similarly, in future developments the reference indoor design temperature could be varied depending on the climate in order to map with more accuracy the effective cooling opportunity.

Nevertheless, the categories of intervention envisaged by applying the proposed methodology are congruent and in line with the results of the post-occupancy evaluation and the level of use of the strategies and systems in the buildings. However, as outlined above, limitations are encountered in the difficulty for these maps to represent local climatic conditions and site microclimate. Therefore, following the initial climatic feasibility analysis through maps, it is important to undertake a more detailed climate and site analysis to fully understand the seasonal and diurnal strategic potential of the local climate.

7. Conclusion

New applicability maps and a climate classification of the potential for downdraught cooling in U.S. have been presented in this paper. The developed maps and classification have been based on (DBT–WBT), cooling degree hours and (26ºC-WBT) indexes.

Using a bioclimatic approach, the potential use of downdraught cooling was analyzed in four counties and the results showed that the map of intervention categories developed concurred with the symmetric analysis of Givoni for evaporative cooling, validating the usefulness of the proposed maps.

Four regions were investigated, covering the very hot and dry summers as well as the Mediterranean climate. The mapped areas show the potential for the use of different variants of downdraught cooling systems.

The results indicate the applicability of different PDEC systems in varying climatic regions and provide a preliminary evaluation of the opportunity of using downdraught cooling systems as an alternative or a complement to conventional air-conditioning systems. The study also highlights that in certain climates where the need for cooling is low, the opportunity for cooling provided by direct evaporation can be high, due to WBTs being sufficiently low to produce a cooling effect and potentially deal with the totality of the cooling loads; where the need for cooling is high, the cooling opportunity can result low, due to WBTs being very close to the set indoor design temperature of 26ºC.

The applicability maps and classification are intended to give designers and decision makers a useful and quick method to assess the potential applicability of downdraught cooling systems in the U.S.

Although this climate classification is developed for downdraught cooling strategies and it is not possible to consider all the climate parameters for all applications and all situations, it is envisaged that future developments could include varying upper threshold indoor temperatures for the calculation of the cooling opportunity currently represented by the index (26ºC-WBT).

Additionally, as previous studies show, the design of the PDEC system has a direct impact on the cooling performance. The type of the water supply system, dimensions of the cooling tower and the outdoor wind speed are another factors that influence airflow rate supplied to the indoor, thus, impacting the overall cooling effectiveness of the PDEC and eventually indoor thermal comfort. These are future research activities that could be carried out regarding to this topic.

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Highlights

- New applicability maps of the potential for downdraught cooling in U.S.
- Classification has been based on DBT–WBT, cooling degree hours and 26ºC-WBT indexes.
- Four buildings showed that the applicability categories and maps are validated.
- Climate zones for downdraught cooling application in the US is defined.