Passive Cooling Applicability Mapping: A tool for designers

Vallejo, J., Ford, B., Schiano-Phan, R. and Aparicio-Ruiz, P.

A paper presented at the Passive Low Energy Architecture Conference 2018, Hong Kong, 10 - 12 Dec 2018.

Passive Cooling Applicability Mapping
A tool for designers

JUAN VALLEJO[1], BRIAN FORD[1], ROSA SCHIANO-PHAN[2], PABLO APARICIO RUIZ[3]

[1]NaturalCooling Ltd, UK
[2]University of Westminster, London, UK
[3]University of Seville, Spain

The applicability of passive cooling methods has been a recurring subject in architectural engineering science. The integration of these methods in architecture often requires feasibility studies and, in most cases, a deep knowledge of the climatic conditions is required to succeed in this task. The number of parameters to be evaluated will depend on the complexity of the cooling system, the physics involved and the context. This paper addresses the climatic applicability of convective and evaporative cooling systems in the context of United States (US) through the creation of a series of applicability maps deriving from processed climate data. This work is a revision of the climatic maps for downdraught cooling developed in Europe and in China with an extension to evaluate the opportunity for natural ventilation. More specifically, the studied cooling solutions are: Natural Convective Cooling (NCC), Passive Evaporative Cooling (PEC), and Active Downdraught Cooling (ADC). The maps obtained demonstrate the strong potential for the use of passive evaporative and convective cooling solutions in the US to overcome the current dependency on mechanical systems.

1. INTRODUCTION

Global demand for cooling is increasing at a spectacular rate. In 2010-11 world sales of air-conditioning went up by 13% [1]. Data from 2016 [2] indicates that in the US 87% of all buildings are air-conditioned, and that air conditioning represents 42% of the peak load. In India and China, summer demand for power outstrips supply, resulting in rationing and the closure of factories and offices. Investment in renewables is increasing, but new fossil fuel power stations are still coming on stream every year.

Alternatives to conventional air-conditioning are needed urgently. The rise in demand for air-conditioning in the US, and the current dependency on it, is unsustainable. And yet the natural environment of the US is not as inhospitable as one might think. This paper presents results from an investigation into both the demand for cooling and the applicability of a range of passive cooling techniques across the whole of the country.

2. BACKGROUND

At early stages in the design process, speedy and robust assessments of feasibility are enhanced by reference to reliable sources of weather data and an understanding of the building use. Weather data plotted on psychrometric charts can promote rapid interpretation to support strategic decision making. Such plots can help to define both the need for cooling and the opportunity for different passive cooling strategies. The combination of 'need' and 'opportunity' can provide the basis for determining 'applicability' of a specific passive cooling technique.

Interactive psychrometric charts are accessible through web and desktop tools, mostly part of climate analysis software packages like Climate Consultant, Climate Tool or Ladybug Tools. By integrating the theory of psychometrics using Szokolay's [3] methods, these tools compare the climatic data against an 'extended' comfort zone for environments with evaporative cooling systems.

Applicability maps, instead, allow the evaluation of passive cooling techniques at a larger geographical scale without the need of accessing multiple weather data. Previous work has published maps which have been constructed to communicate both the 'need' for cooling and the 'opportunity' for different climatic regions. A group at the University of Seville, Department of Energy Engineering, pioneered the definition of these maps, initially for Spain [4] and subsequently for the whole of Europe [5]. A similar approach has also been applied to map the applicability of different downdraught cooling options in China [6] and recently in the US [7], but these applied the original methodology and did not consider convective cooling.

In the US, the application of passive evaporative cooling methods in contemporary architecture is not new, and the design integration and performance evaluation of a series of built precedents have already been explained [4], [8]. The assessment and mapping methodology previously used has been revisited and expanded in this work to allow a full applicability evaluation of NCC, NEC and ADC.

The entire process was taken to a higher degree of resolution, now dealing with hourly data instead of daily average data by means of big data processing techniques.

The third generation of Typical Meteorological Year climate data (TMY3), which derives from the 1961-1990 and 1991-2005 National Solar Radiation Data Base (NSRDB) archives, was obtained for 1020 locations in the US and post-processed to generate the applicability maps. The applicability in counties without climate data is determined using an interpolation methodology [9] by means of the geographical distance between the closest meteorological stations, latitude, altitude and proximity to the sea.

3. THE MAPPING METHODOLOGY

The 'need' (or demand) for cooling is based on a combination of climatic factors, and building design characteristics (uses, occupancy density, equipment & lighting). Preliminary assessments of cooling needs are often simply related to climatic factors and can be expressed as the number of cooling hours (CH) for a location. The number of cooling hours represent the number of hours when cooling might be needed and can be determined directly from hourly weather data for the location, or from maps for the region.

Assessment of the 'opportunity' of applying different passive cooling options strategies in a specific location will be determined by climatic factors alone (including dry and wet bulb temperatures and inside-outside temperature difference). The opportunity of a passive cooling strategy for a location can be expressed in terms of a temperature difference 'range' (ΔT).

The 'need' for cooling in a location may be 'low' or 'high', just as the 'opportunity' for a particular passive cooling technique may be 'low' or 'high'. The 'applicability' of a particular technique can therefore be considered to be a multiple of 'need' and 'opportunity', and this is the basis for the mapping of the applicability of cooling by natural convection, evaporation and active downdraught described in this paper. Essentially:

$$\text{APPLICABILITY} = \text{NEED (CH)} \times \text{OPPORTUNITY } (\Delta T) \quad (1)$$

4. NATURAL CONVECTIVE COOLING (NCC)

Natural ventilation is a recurrent strategy to provide healthy and comfortable internal environments. Its capacity to reduce indoor temperature through convection (convective cooling) is also widely appreciated and presents significant benefits against mechanical systems: reduced carbon emissions (mechanical ventilation can represent 25-35% of electrical energy use in buildings), reduced capital cost (mechanical ventilation can add 10% to the capital cost) and reduced maintenance cost (mechanical ventilation can double lifecycle costs) [10].

Assuming a design indoor temperature of 26°C, equal to the upper limit of a thermal comfort zone for indoor environments with elevated high humidity and air velocity [11], the climatic applicability of convective cooling can be directly determined by the indoor-to-outdoor temperature depression, 26°C-DBT. This index derives from the sensible cooling equation [12], which determines the amount of energy needed to reduce the temperature of a volume of air keeping its moisture content constant. The equivalent cooling is thus directly proportional to the indoor-to-outdoor air temperature difference and responds to the question: *how much cooler is the climate with respect to indoor temperature?* 26°C-DBT has been determined for each hour of the analysis period and the average values are mapped in Fig. 1. The map suggests a prevailing range of indoor-to-outdoor air temperature depression between 3°C and 9°C, with cooler areas referring to the Northern counties and high altitudes. The displayed scale responds to the following criteria: $\Delta T<3$ (low), $3<\Delta T<6$ (medium-low), $6<\Delta T<9$ (medium-high) and $\Delta T>9$ (high).

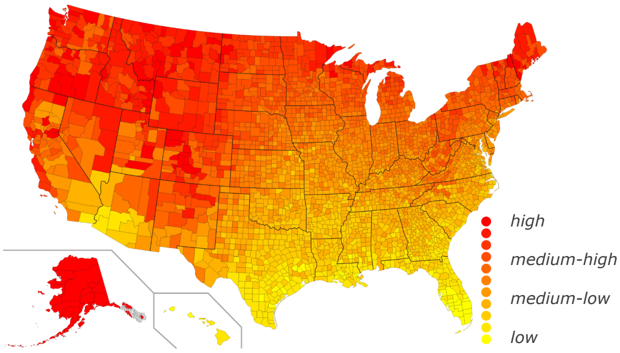

Figure 1: Natural convective cooling applicability. Determined from 26°C-DBT.

In addition to the above index to evaluate the NCC applicability, a second index determining average daily temperature fluctuation was obtained to complement it. Night ventilation is a recurring strategy to release the heat received and often absorbed by the building mass, and a higher temperature drop at night increases convective heat exchange and internal heat losses. Fig. 2 maps the average day-to-night temperature depression DBTmax-DBTmin and suggests the opportunity for night ventilation as well as a good potential for thermal mass (when coupled with night ventilation) as a strategy to reduce indoor peak temperatures. The results suggest a good opportunity for night ventilation in most counties, presenting a mean range of DBTmax-DBTmin between 10°C and 20°C with high applicability in Western counties where altitude is typically higher than 1000 meters above the sea level. The displayed scale responds to the following criteria: ΔT<5 (low), 5<ΔT<10 (medium-low), 10<ΔT<15 (medium-high) and ΔT>15 (high).

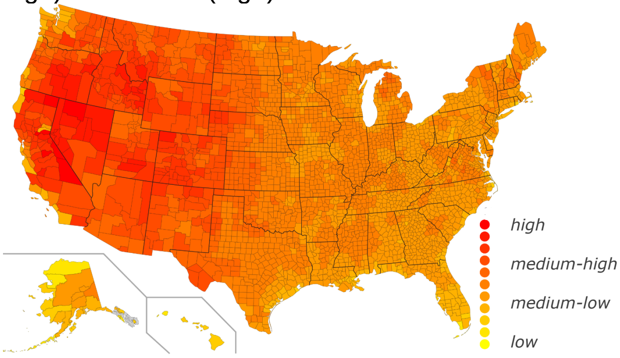

Figure 2: Opportunity for night ventilation. Determined from average DBTmax-DBTmin.

The above maps provide sufficient information to evaluate convective cooling methods. The outcome from these maps is promising and concludes that 70% of the counties in US (presenting high applicability) could overcome overheating problems in buildings with a good natural ventilation strategy and without the need of mechanical systems.

5. PASSIVE EVAPORATIVE COOLING (PEC)

Assuming the same design indoor temperature, the need for cooling can be determined by the number of hours (h) when DBT>26°C for a theoretical warm period from June to September (presenting a maximum number of hours of 2928). The results for each county is mapped in Fig. 3. The map suggests a higher demand in areas with lower latitudes and altitudes, in other words, the Southeast counties from Texas to Florida, Southern California and Arizona. The displayed scale responds to the following criteria: h<750 (low), 750<h<1500 (medium-low), 1500<h<2250 (medium-high) and h>2250 (high).

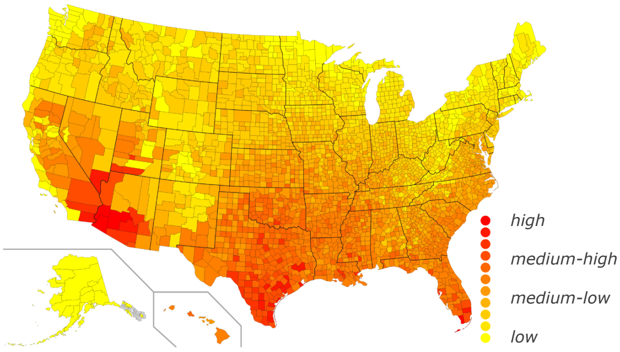

Figure 3: Passive evaporative cooling need. Determined from DBT>26°C.

The opportunity or efficiency of an evaporative cooling method derives from the wet bulb temperature depression and responds to the question: *how dry is the climate?* This question has been addressed in three different approaches that adapt to different contexts.

- The first approach determines DBT-WBT for each hour of the analysis period and the average values are mapped in Fig. 4. The results obtained broadly represent the humidity of the climate with no differentiation between day a night. The map also suggests a prevailing range of DBT-WBT between 3°C and 6°C, with dryer areas referring to the Western counties, and highlighting an evident relation with the altitude above the sea level. The displayed scale responds to the following criteria: ΔT<3 (low), 3<ΔT<6 (medium-low), 6<ΔT<9 (medium-high) and ΔT>9 (high).
- The second approach determines DBT-WBT when DBT>26°C. This index represents the maximum opportunity by mapping the wet bulb depression at the warmer hours of the day. It is indeed addressing PEC opportunity in the outdoor environment when most needed. The results mapped in Fig. 5 extends the high opportunity also to Eastern counties and the prevailing range of DBT-WBT at the warmer hours now increases from 4°C to 8°C. The displayed scale responds to the following criteria: ΔT<4 (low), 4<ΔT<8 (medium-low), 8<ΔT<12 (medium-high) and ΔT>12 (high).
- The third approach considers the previously used design indoor temperature of 26°C to determine the wet bulb depression. As with the maps created for Europe and China, 26°C-WBT indicates the opportunity to reduce cooling demand in indoor spaces with a PEC system that theoretically could supply air at wet bulb temperature. The results mapped in Fig. 6 suggest that PEC opportunity could be extended even in the colder and more humid regions of North-eastern US when a theoretical indoor temperature is achieved as a result of the internal and solar gains. The displayed scale responds to the following criteria: ΔT<3 (low), 3<ΔT<6 (medium-low), 6<ΔT<9 (medium-high) and ΔT >9 (high).

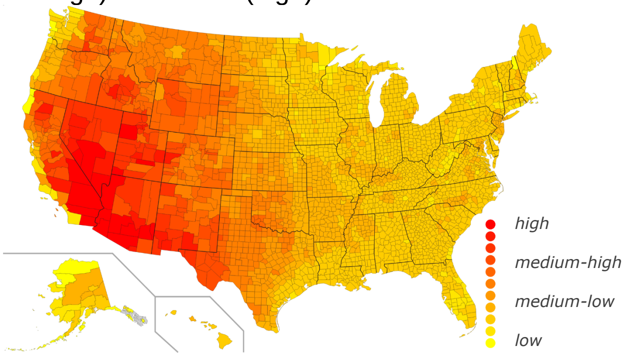

Figure 4: Passive evaporative cooling opportunity (I). Determined from DBT-WBT.

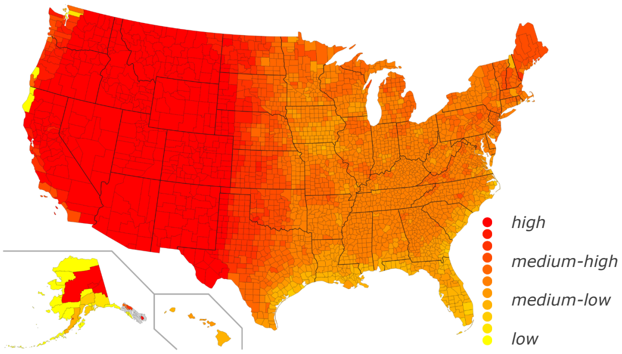

Figure 5: Passive evaporative cooling opportunity (II). Determined from DBT-WBT when DBT>26°C.

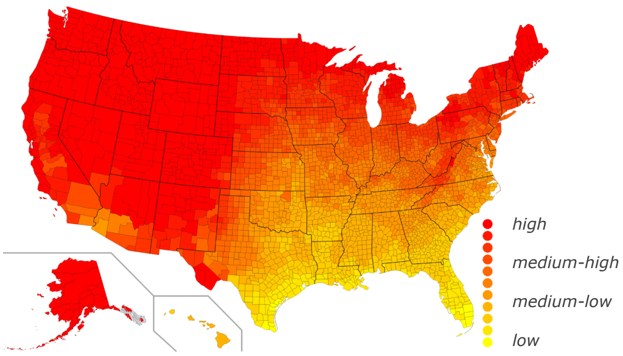

Figure 6: Passive evaporative cooling opportunity (III). Determined from 26°C-WBT.

The above maps provide sufficient information to evaluate separately need and opportunity for PEC systems in early stages. As both indexes are equally important, higher number of warm hours (demand) and higher wet bulb temperature depression (opportunity) yield high applicability. The maps shown in Figs. 7-9 combine PEC demand with each of the opportunity indices above described to determine PEC applicability as in Equation (1), equivalent to the cooling degree-hours [hours ×°C]. It is important to look at the three maps for a better understanding of PEC viability under different contexts. The combined results suggest a medium to high applicability in South and Southwest regions in the US for outdoor spaces and extended high applicability region towards the North for indoor spaces. The maps conclude that 30% of the US counties present optimal climatic environmental conditions for the integration of passive evaporative cooling systems in architecture. These results are satisfactory and confirm that alternative passive methods to the 'default' use of mechanical systems are very valid and present a huge potential for expansion to overcome the recurring increase in greenhouse gas emissions during the last decade [13].

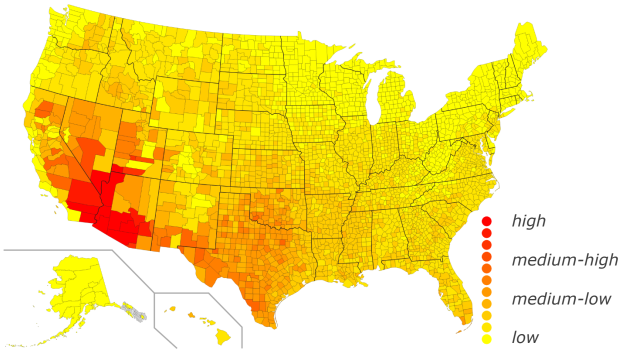

Figure 7: Passive evaporative cooling applicability (I). Determined from CH x [DBT-WBT].

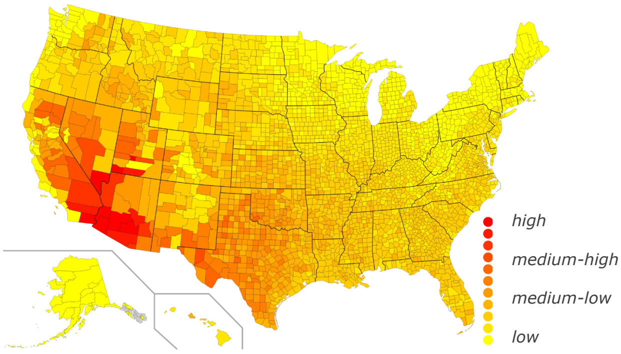

Figure 8: Passive evaporative cooling applicability (II). Determined from CH x [DBT-WBT when DBT>26°C].

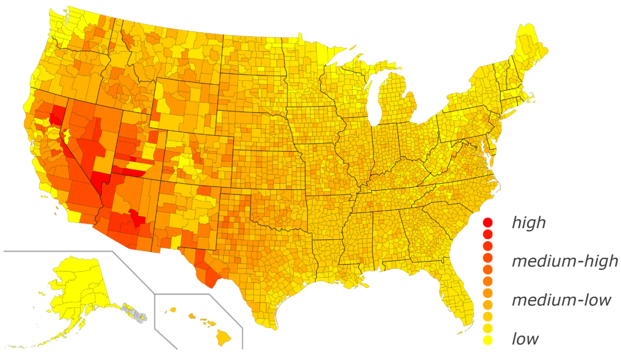

Figure 9: Passive evaporative cooling applicability (III). Determined from CH x [26°C-WBT].

6. ACTIVE DOWNDRAUGHT COOLING (ADC)

Active downdraught cooling becomes an environment-friendly solution to climates with warm and humid conditions presenting low PEC applicability. It is achieved by using chilled water cooling coils or panels exposed to a warm internal environment, thus inducing a natural indoor air movement (downdraught). Although it relies on mechanical cooling, it avoids the need for fans, which can represent an energy saving of 25–35% of the electrical load in non-domestic buildings. [14].

Cooling in ADC systems is achieved by convective heat exchange and no evaporation takes place. Although ADC is applicable for both humid and dry climates and air moisture content does not have a significant impact on the cooling delivered, the applicability assessment proposed in this paper prioritises passive systems over active systems. In other words, ADC applicability is inversely proportional to PEC applicability.

The need for active downdraught cooling is determined as with PEC, thus by defining the number of hours (h) when DBT>26°C for a theoretical warm period from June to September. The results for each county are mapped again in Fig. 10 and the same graphical interpretation and scale criteria applies as with PEC applicability.

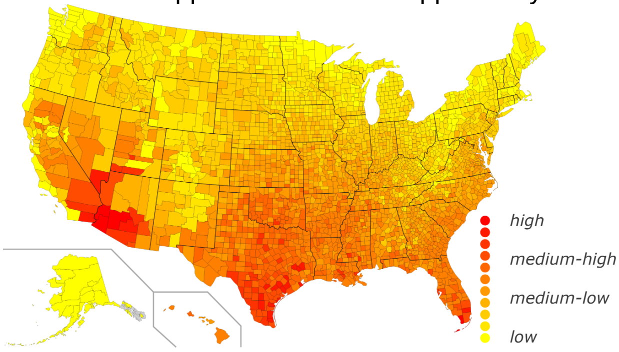

Figure 10: Passive evaporative cooling need. Determined from DBT>26°C.

The opportunity or efficiency of an active downdraught cooling method is directly proportional to the temperature difference between the room and the coil temperature for a convective heat exchange. This characteristic makes ADC methods less coupled to climate and reaffirms its potential applicability for both humid and dry environments. To evaluate ADC opportunity the index coil-to-room temperature depression is determined together with a complementary index to prioritise ADC opportunity on humid climates. This second index responds to the question: *how humid is the climate?*

- The first index determines a potential maximum coil-to-room temperature depression. The room temperature is the design indoor temperature equal to 26°C. The coil temperature is set to the minimum temperature at which condensation on the coil surface won't happen. In theory, the on-coil water temperature should be slightly above the dew-point temperature (DPT), but for simplicity it is considered equal to DPT. This first opportunity index is thus determined from 26°C-DPT and results are mapped in Fig. 11. The map suggests a mean range of coil-to-indoor air temperature depression between 10°C and 15°C. It is by about 4 degrees higher than PEC opportunity (III) index (26-WBT) and its opportunity extends to most US area. The displayed scale responds to the following criteria: ΔT<3 (low), 3<ΔT<6 (medium-low), 6<ΔT<9 (medium-high) and ΔT>9 (high).
- The second index is determined from DBT-WBT as in PEC opportunity index (I). In this case, and in order to prioritise ADC opportunity in humid climates, lower wet bulb temperature depressions are associated to high ADC opportunity. As in Fig. 4, the results obtained and mapped in Fig. 12 illustrate the average humidity of the climate represented in the inverse ranking of opportunity. The map also suggests a prevailing range of DBT-WBT between 3°C and 6°C, highlighting more humid areas in Eastern counties with lower altitudes. The displayed scale follows the criteria: ΔT<3 (high), 3<ΔT<6 (medium - high), 6<ΔT<9 (medium-low) and ΔT>9 (low).

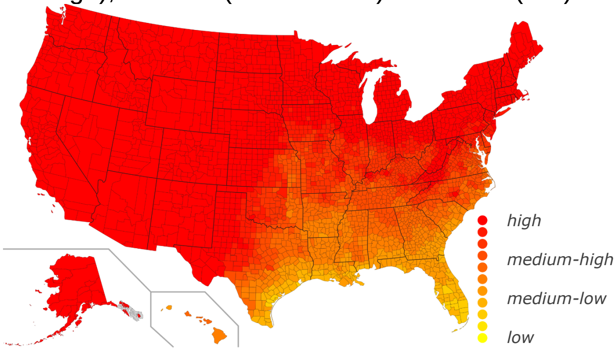

Figure 11: Active downdraught cooling opportunity (I). Determined from 26°C-DPT.

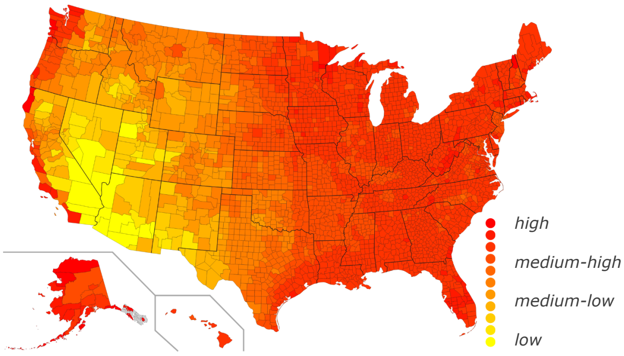

Figure 12: Active downdraught cooling opportunity (II). Determined from DBT-WBT.

The above maps provide relevant information to evaluate separately demand and opportunity for ADC systems in early design stages. Demand and opportunity (I) indices are directly proportional to ADC applicability: higher number of warm hours (demand) and higher coil-to-indoor temperature depression (opportunity) yield to high applicability. ADC opportunity (II) is, however, inversely proportional to ADC applicability as lower wet bulb temperatures depression yields to higher applicability in order to promote the use of PEC methods in dryer climates. The maps shown in Fig. 13 and Fig. 14 combine ADC need with each of the opportunity indexes above described to determine ADC applicability from Equation (1) and Equation (2):

APPLICABILITY = NEED (CH) ÷ OPPORTUNITY (ΔT) (2)

The combined results suggest that in principle, ADC is applicable in most US, presenting the highest applicability in South and Southwest regions in the US (Fig. 13). However, this strategy should be prioritised over PEC methods only in South-eastern regions as suggested in Fig. 14.

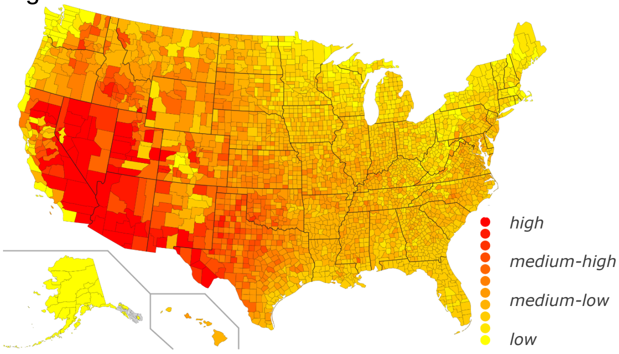

Figure 13: Active downdraught cooling applicability (I). Defined from CH x [26°C-DPT].

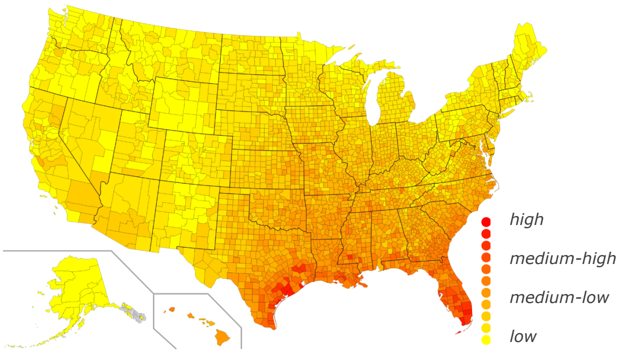

Figure 14: Active downdraught cooling applicability (II). Defined from CH ÷ [DBT-WBT].

7. CONCLUSION

The proposed method and its application provide a reliable set of maps to determine the applicability of Natural Convective Cooling, Passive Evaporative Cooling and Active Downdraught Cooling systems in the USA at early design stages. The work also defines a methodology to assess the applicability of each cooling method with the highest rigour through a series of indexes that derive from the physics involved during the cooling process and adapt to different contexts. This methodology can be applied to any location in the world and aims to set the base for a future standardised method to assess the applicability of passive cooling techniques in architecture in a simple and accurate manner.

Hence, these maps target architects and product designers with limited knowledge in this field to, for instance, suggest the most suitable cooling strategy to overcome overheating problems or evaluate the market opportunity of a novel evaporative cooling product.

The results obtained are promising and suggest a large potential for the use of passive evaporative (PEC) and convective cooling solutions in the US. In fact, from the climatic data available it can be concluded that more than 50% of the counties in the US are eligible for the application of PEC methods and more than 70% of the counties could overcome overheating problems in buildings with a good natural ventilation strategy and without the need of mechanical systems. Although the presented methodology does not include all the related criteria for applicability (i.e. building geometry, internal heat gains, water availability, etc), the maps are still a robust and useful tool that supports the development of alternative evaporative and convective cooling systems for architecture, demonstrating the high potential of these systems for improving comfort conditions and overcome the current dependency on mechanical systems.

REFERENCES

1. Cox, S. (2010). *Losing our Cool*; The New Press, NY.
2. Commercial Buildings Energy Consumption Survey (CBECS). Metadata update 2017 (Aug).
3. Szokolay, S. V. (2008). Introduction to architectural science : the basis of sustainable design. Amsterdam ; London, Architectural.
4. Ford, B., Schiano-Phan, R. & Francis, E. (2010). *The Architecture & Engineering of Downdraught Cooling: a design sourcebook*, PHDC Press.
5. Salmerón, J. M., Sánchez, F. J., Sánchez, J., Álvarez, S., Molina, J. L. & Salmerón, R. (2012). *Climatic applicability of downdraught cooling in Europe.* Architectural Science Review, 55, 259-272.
6. Xuan, H. & Ford, B. (2012). *Climatic applicability of downdraught cooling in China.* Architectural Science Review Special Issue.
7. Aparicio-Ruiz, P., Schiano-Phan, R. and Salmeron-Lissen, J.M. 2018. *Climatic applicability of downdraught evaporative cooling in the USA. Building and Environment.* 136, pp. 162-176.
8. Schiano-Phan, R. (2012). *Post-occupancy evaluation of non-domestic buildings using passive downdraught evaporative cooling in south-west USA.* Architectural Science Review 55(4): 320-340.
9. De La Flor, F. J. S., Domínguez, S. Á., Félix, J. L. M. & Falcón, R. G. (2008). *Climatic zoning and its application to Spanish building energy performance regulations.* Energy and Buildings, 40, 1984-1990.
10. K. J. Lomas, M. J. Cook & C. A. Short (2009) *Commissioning hybrid advanced naturally ventilated buildings: a US case study*. Building Research & Information, 37:4, 397-412.
11. Givoni, B. (1994). *Passive and low energy cooling of buildings*, New York, Van Nostrand Reinhold.
12. ASHRAE (2013). *ASHRAE Handbook: Fundamentals 2013*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

13. IPCC (2014). *Climate Change 2014: Synthesis Report*. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the IPCC.
14. Short, C.A. and Cook, M.J. (2005). *Design guidance for naturally ventilated theatres*. Building Services Engineering Research and Technology, Hodder Arnold, 26 (3), September, pp. 259-270.