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Development of an enthalpy-based index to assess climatic potential for ventilative cooling of buildings: an Australian example

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Abstract

Ventilative Cooling is a promising technique to improve the energy efficiency of buildings through reduced need for mechanical cooling to maintain thermal comfort. To assess the feasibility of Ventilative Cooling in a specific location, it is useful for designers to be able to evaluate the climate potential for cooling. This paper describes a new and enhanced version of the Climatic Cooling Potential (CCP) method, which is a simplified method to evaluate the climate potential for passive cooling that does not require detailed knowledge of the building characteristics. The proposed Enthalpy Climatic Cooling Potential (CCP_h) integrates humidity into the climate evaluation, using the enthalpy difference between indoors and outdoors, instead of the temperature difference. It accounts for latent heat, providing a better estimate of locations where the use of outside air will be beneficial from an energy perspective. The methods were compared by mapping the Ventilative Cooling potential for the Australian climate, using weather data from 391 weather stations across Australia. Results showed that most of the highly populated cities in the south of Australia have a climate suitable for Ventilative Cooling. This is true even in the summer period, although the area where the climate is beneficial is significantly larger during the shoulder seasons and winter. The analysis

showed that using the CCP index, rather than the new CCP_h index, can lead to an under-estimation of the cooling potential during dry winters and an over-estimation during humid summers, due to the contribution of the latent heat.

Keywords: Ventilative Cooling, climatic cooling potential, enthalpy, climate analysis, passive cooling, Australian climate

Nomenclature

$\dot{m}$	Mass flow rate (kg/h)
ϕ	Relative humidity (%)
ACH	Air changes per hour (1/h)
h_b	Enthalpy of the indoor air (kJ/kg)
h_e	Enthalpy of the outdoor air (kJ/kg)
$m_{n,t}$	Boolean variable that activates Ventilative Cooling
N	Number of days considered for calculation of the CCP and CCP_h indices
n	Day
P	Barometric pressure of the atmospheric air (kPa)
P_{ws}	Saturation vapour pressure (Pa)
Q	Daily Ventilative Cooling energy (kJ)
t	Time of the day
t_f	Final time of night-time ventilation
t_i	Initial time of night-time ventilation
T	Dry-bulb temperature (°C)
T_b	Dry-bulb indoor air temperature (°C)
$T_{b,m}$	Comfort temperature as defined by Standard ISO 7730 (°C)
$T_{b,s}$	Indoor temperature swing (°C)
T_{db}	Air dry-bulb temperature (°C)
T_e	Dry-bulb outdoor air temperature (°C)
V	Volume of the enclosed space (m ³)
Δh_c	Enthalpy difference threshold value (kJ/kg)
ΔT_c	Temperature difference threshold value (°C)
ρ	Air density (kg/m ³)

1 Introduction

The building sector represents a large portion of total global energy consumption; estimates of its contribution vary from approximately 30 to 45% of total national energy demand depending on the country [1]. Population growth, increased implementation of building services, rising

expectations regarding thermal comfort conditions and the increase in time that individuals spend indoors have all contributed to a trend of increasing energy consumption in this sector.

In Australia, the energy consumed by the heating, ventilation and air conditioning (HVAC) system in a typical office building is the largest single end-use of electricity, corresponding to around 40% of the total buildings energy consumption; approximately 27% of a buildings energy consumption is attributed to cooling [2]. The demand for cooling is expected to rise over time, due to an increase in the comfort expectations of building occupants [1,2,3] . This expected increase in cooling energy consumption has the potential to be mitigated via cooling strategies that use little or no power, such as Ventilative Cooling.

Numerous studies have described the types and efficacy of passive cooling techniques; a thorough review of these studies can be found in [4]. An extensive review of passive and active cooling methods was presented in [5]. The authors described the technical accessibility, reliability and economic feasibility of various cooling methods for residential buildings, and provided an assessment of the temperature decrease for each cooling method within a typical-size dwelling. A decision support tool was developed to identify the most appropriate cooling method based on the climate, building status and investment cost, and demonstrated for the Mexican context. It was found that certain active and passive cooling methods had the potential to be employed at a national level in the residential sector and would be expected to result in significant energy savings. A summary of cooling related research in office buildings in the past twenty-five years was presented in [6]. The review focused on cooling systems and strategies specifically related to office buildings façades, and found an increasing scientific interest in cooling research. A need for further research was identified in the assessment of the application and architectural integration of cooling systems.

The current paper focused on Ventilative Cooling, which utilises the cooling capacity of outdoor air via natural or mechanical ventilation (or a combination of both) to decrease or eliminate the cooling load from the air conditioning system, while maintaining indoor thermal comfort [7]. A successful example of an hybrid ventilative cooling system, which combined natural ventilation with diffuse ceiling inlet and thermally activated building systems can be found in [8].

Recent studies, for example [9], have highlighted that even in cold climates there is a risk of overheating due to the more stringent requirements for modern buildings in terms of insulation and air-tightness. Appropriately controlling air exchange with the outdoor ambient air can reduce overheating in cold [10,11,12] climates and reduce the cooling consumption in warmer climates [12,13].

Ventilative Cooling mixes outdoor with indoor air to remove heat from the space and can be employed at any time when the outdoor conditions are favourable. However, the potential for Ventilative Cooling during the day is often limited by the unsuitability of outdoor conditions [14]. Night-time Ventilative Cooling has proven to be effective in regions with high diurnal temperature fluctuations, as the outdoor air can be used to cool a buildings thermal mass. This leads to an attenuation of the indoor temperature rise the next day [4,15] and thereby reduces the air-conditioning demand or peak load. Despite the existing evidence that Ventilative Cooling techniques can significantly help building energy efficiency and occupants satisfaction, its application in commercial buildings is still hindered due to perceived risks on its implementation and effectiveness [16,17].

The effectiveness of Ventilative Cooling depends on the local site conditions, which change seasonally as well as daily. Thus, to assess whether a building could potentially benefit from the implementation of a Ventilative Cooling technology in a specific geographic location, the

climate conditions need to be evaluated carefully. Typically, the degree-hours or degree-days method has been employed to provide an indication of the severity of a climate [18]. Such methods use a 'base temperature' which is the maximum outdoor temperature at which mechanical cooling systems are not expected to be required to maintain comfort conditions. The base temperature varies as a function of the building thermal characteristics and internal loads. However, the majority of methods which use degree-days consider two constant temperature thresholds, one for heating and one for cooling.

The Climatic Cooling Potential (CCP) was developed [19] in order to provide a better evaluation of the extent to which a climate provides favourable conditions for Ventilative Cooling than that offered using the degree-days method. The CCP was defined as the sum of the hourly difference between indoor and outdoor temperature over a specific time period. The indoor temperature profile was estimated using the assumption that it oscillates within a fixed comfort temperature range, to approximate the thermal inertia of a building.

Other studies have investigated methods to evaluate whether a climate is suitable for passive cooling strategies without *a-priori* knowledge of the building, by modifying the degree-hours method to define the maximum number of hours when Ventilative Cooling could ideally be employed in a building for a given climate [20,21,22,23,24,25,26,27]. In [20] the outdoor temperature was arranged into temperature bins and compared with a constant base temperature to enable the estimation of the benefits in terms of cooling load reduction from using an economiser in the HVAC system,. Numerous studies [21,22,23,24,25,26] have used both indoor thermal comfort and outdoor weather conditions constraints to identify when Ventilative Cooling can be utilised. Some of them have implemented a higher temperature limit based on adaptive comfort models [28,29], while others have accounted for humidity [22,23,24]. In regard to the lower temperature limit, some studies have used the adaptive model [21], while others have used a fixed value [22,23]. Time-varying schedules have also been

considered by [24]; an application of this method was provided in [30]. A tool to assess the potential for passive cooling strategies in a composite climate in India was developed by [27], based on the percentage of time the outdoor dry-bulb temperature and the humidity ratio were within thermal comfort boundaries according to the Tropical Summer Index (TSI) developed by [31].

The aforementioned methods, particularly [18,19,24] under-represent the potential for natural ventilation, since warm indoor conditions could still benefit from the use of Ventilative Cooling even if the outdoor temperature is colder than is acceptable indoors. Other methods have ignored the lower boundary temperature constraint [25,26], in order to maximise the free cooling potential of a certain climate. Constraints on wind pressure, stack effect, noise and pollutants have been employed as additional criteria in [25].

The CCP has been redefined to develop a new index named Useful Cooling Potential (UCP) [32,33], in order to estimate the direct reduction in a building's cooling demand when using a passive Ventilative Cooling system. The UCP facilitates quantification of cooling demand reductions due to a Ventilative Cooling implementation by comparing the sensible cooling provided by Ventilative Cooling with a reference system that introduces air to the building at a reference temperature. In [34] a method to estimate the heating and cooling demand and potential cooling demand reductions through Ventilative Cooling was developed based on the degree-days method. Both methods requires some *a-priori* knowledge of the building or system, which prevents a complete generalisation of the method.

Other researchers have evaluated the climatic potential for Ventilative Cooling technology and the consequent improvement of comfort levels with minimal building information [19,35]. For example, in [35] a new tool implementing a climate suitability analysis methodology with the capability to consider an adaptive thermal comfort option was developed.

While quite extensive work has been undertaken in evaluating the climate potential for the application of Ventilative Cooling technologies, and elegant indices, such as the Climatic Cooling Potential, have been developed, there remains a gap in current research. To the best of the authors' knowledge no climatic index has been extended to take into account both sensible and latent heat in the air exchange process. This is of particular importance in warm and humid climates, where the outdoor humidity might play an important role in determining the cooling potential of the climate, especially if the enthalpy of the outdoor air is similar or higher than the indoor air, despite a lower temperature. During winter, when the air is normally drier due to the lower air temperature, the Ventilative Cooling benefit can be only considered if humidity is included in the index calculation.

To this end, the current paper proposes a novel index, the Enthalpy-based Climatic Cooling Potential, or CCP_h . This study presents the methodology to estimate this index, its practical significance and an example of its application. This is particularly important in determining the complete energy contribution that the climate can provide in terms of both sensible and latent heat, resulting in a consequent potential reduction of a building's energy consumption. Since no studies appear to have been undertaken to map the Australian climate with respect to Ventilative Cooling potential, Australia was used as a demonstrative case study. The CCP_h index was calculated to map the appropriateness of the Australian climate for Ventilative Cooling throughout the year. This paper details the methodology employed to calculate the CCP_h in Section 2. Results, associated commentary and validation are presented in Section 3, and Conclusions are presented in Section 4.

2 Methodology

The present study proposes a new index, the enthalpy-based Climatic Cooling Potential (CCP_h), which aims to improve the existing Climatic Cooling Potential index by representing the

cumulative difference between the outdoor and indoor enthalpy. This provides a better representation of the potential energy saving that a building could achieve by utilising a Ventilative Cooling technology.

To achieve this objective, the weather data and indoor conditions must include humidity in addition to dry-bulb temperature.

2.1 Climatic Cooling Potential (CCP) and Enthalpy Climatic Cooling Potential (CCP_h)

The CCP index was calculated using the definition from [19] so as to map the Australian climate using a method that is directly comparable with the results previously published for Europe. The CCP index was therefore calculated using Eq. 1:

$$CCP = \frac{1}{N} \sum_{n=1}^N \sum_{t=t_i}^{t_f} m_{n,t} (T_{b,n,t} - T_{e,n,t}) \begin{cases} m_{n,t} = 1 & \text{if } T_{b,n,t} - T_{e,n,t} \geq \Delta T_c \\ m_{n,t} = 0 & \text{otherwise} \end{cases} \quad (1)$$

Where t represents the time of day, t_i and t_f denotes the initial and the final time of night-time ventilation and ΔT_c is the threshold value of the temperature difference that allows Ventilative Cooling to occur.

For comparison purposes the CCP index was calculated using only $\Delta T_c = 3K$, and the options of applying Ventilative Cooling for 24 hours per day (summing the CCP index over the entire dataset) or only during the night (from $t_i = 1900$ h to $t_f = 0700$ h), were assessed. The night-time-only ventilation index was calculated and is presented in Figure 4c) to facilitate direct comparison of the results with those presented in [19]. However, there are no inherent time limitations on the application of a Ventilative Cooling technology that would restrict daytime use.

In the present study, the CCP index was extended to better represent the potential energy that can be offset by the Ventilative Cooling technology, by calculating the cooling potential based

on the enthalpy difference between indoor and outdoor conditions and thereby incorporating the effects of differences in humidity levels. The enthalpy of the indoor and outdoor air can be calculated using Eq. 2, as defined in [36]:

$$h = 1.006 \cdot T + W(2051 + 1.86 \cdot T) \quad (2)$$

Where h is the air enthalpy (kJ/kg), T is the air dry-bulb temperature ($^{\circ}\text{C}$), W is the humidity ratio, The saturation vapour pressure (P_{ws}) can be calculated using the August-Roche-Magnus approximation in Eq. 3, to compute the humidity ratio at defined temperature and relative humidity conditions:

$$P_{ws} = 0.61094 \exp\left(\frac{17.625 \cdot T}{T + 243.04}\right) \quad (3)$$

Following calculation of the indoor and outdoor enthalpies at each time step (h_b and h_e respectively), the Enthalpy Climatic Cooling Potential (CCP_h) index was determined using Eq.4:

$$\text{CCP}_h = \frac{1}{N} \sum_{n=1}^N \sum_{t=t_i}^{t_f} m_{n,t} (h_{b,n,t} - h_{e,n,t}) \begin{cases} m_{n,t} = 1 & \text{if } \begin{cases} T_{b,n,t} - T_{e,n,t} \geq \Delta T_c \\ h_{b,n,t} - h_{e,n,t} \geq \Delta h_c \end{cases} \\ m_{n,t} = 0 & \text{otherwise} \end{cases} \quad (4)$$

Where Δh_c is the threshold value of the enthalpy difference that allows Ventilative Cooling to occur. In this study the CCP_h index was calculated assuming $\Delta h_c = 1$ kJ/kg. This value was chosen to be small (equivalent to 2% relative humidity difference at 24°C) since the constraint ΔT_c is also considered at the same time, ensuring enough sensible cooling to make the ventilation process efficient.

2.2 Climatic Data

To calculate the proposed index, hourly weather data was required as an input. In Australia, the Bureau of Meteorology (BOM) [37] is the national weather, climate and water agency. Observations for all the Australian weather stations are accessible online with half-hourly

temporal resolution. Data is normally available for the previous three days, therefore an automatic script was used to create a complete dataset of the weather data available online. A total of 458 weather stations across Australia were available online at the time of this study. To avoid the influence of distinctive climates, such as islands, and localised outliers, such as reading from weather stations at high altitude, only stations located on the mainland with an elevation lower than 1000m were utilised in the present study. As a result, a total of 391 were used to generate the maps presented in this paper. The dataset was collected between the 1st February 2018 and the 31st January 2019.

It should be noted that in 2018 the annual national mean temperature was 1.14 °C above average and it was the third-warmest year on record. While the nationally-averaged rainfall was 11% below the average for the year [38].

Due to annual or seasonal variabilities and minor incompleteness of the dataset, the use of the BOM observation data for estimating the CCP and CCP_h was validated by comparison with typical year data. The CCP and CCP_h were calculated for Australian capital cities using the relevant Australian Representative Meteorological Year (RMY) climate files [39]. RMY climate files represent the climate for a ‘typical’ year based on a composite of representative months from different years. This validation analysis was limited to the state capitals for simplicity of comparison, as the RMY climate files were not available for all locations.

Australia is characterised by a variety of climates, and there is substantial variation in climate across the country. The Köppen-Geiger climate classification of Australia is shown in Figure 1. A simplistic visual representation of the potential for Ventilative Cooling in Australia is provided in Figure 2. Givoni [42] defined 20°C as the upper threshold for the applicability of night-time Ventilative Cooling. The monthly mean daily minimum temperature for January

2019 is presented in Figure 2a; the values displayed were estimated using linear interpolation between the three closest weather stations [41].

Significant regional variation can be seen in Figure 2a. Monthly mean daily minimum temperatures as high as 29°C were recorded in the central desert region, , while monthly mean daily minimum temperature temperatures as low as 7°C were recorded in some parts of Tasmania. Using the Threshold from Givoni [42], Ventilative Cooling could potentially be used in the great majority of the Australian Capital Cities, with exception of Darwin, where the monthly mean daily minimum temperature exceeded 23°C.

Figure 1 Köppen-Geiger climate classification of Australia, capital cities marked in grey. The map was plotted using data from [40].

Figure 2: a) Monthly mean daily minimum temperatures ($^{\circ}\text{C}$), January 2019. And b) Mean difference between daily minimum and maximum temperature ($^{\circ}\text{C}$), January 2019. Plots are based on data from the Australian Bureau of Meteorology. Weather stations are marked in black and capital cities in purple.

Another key indicator for the applicability of Ventilative Cooling is the difference between the monthly mean daily maximum and minimum temperatures for each location. The mapping of this difference for Australia in January 2019 is presented in Figure 2b. The Southern coastal regions experienced significantly higher temperature variations than northern coastal regions. High variation where also recorded inland across Australia. These two simplistic measures suggest there may be high potential for Ventilative Cooling in many parts of Australia, and particularly in densely populated regions surrounding capital cities (the location of capital cities are shown in Figure 1).

2.3 Building temperature and enthalpy profile

The indoor temperature and enthalpy profiles necessary for the calculation of the CCP and CCP_h indices were calculated using a similar approach to the one presented by Artmann *et al.* [19]. This simplified approach can estimate the effect of thermal energy that is stored or released from building thermal mass on internal air temperature. A variable building temperature profile was defined as in Eq. 5, which oscillates harmonically:

$$T_{b,t} = T_{b,m} + T_{b,s} \cos(2\pi \frac{t-t_i}{24}) \quad (5)$$

Where $T_{b,m}$ is the temperature at the middle of the ISO 7730 standard [43] comfort band and $T_{b,s}$ is the temperature swing that the building is allowed to achieve, in accordance with the ISO 7730 comfort band.

The ISO 7730 standard defines three categories of thermal environments, where each category has a prescribed maximum value for the predicted percentage of dissatisfied (PPD): Category A PPD = 6%; Category B PPD = 10%; and Category C PPD = 15%. In the present study Category B was utilised to define the building temperature swing, similar to [19].

Rather than defining a constant value for $T_{b,m}$ and performing a sensitivity analysis on three levels of $T_{b,s}$, as was done in [8], the present study utilised different values for $T_{b,m}$ and $T_{b,s}$ during the year, in an attempt to comply with the seasonal thermal comfort bands defined by the ISO 7730. The value of $T_{b,m}$ was set equal to 24.5 °C during summer, 23.25 °C in the middle seasons and 22.0 °C during winter, and the value of $T_{b,s}$ was equal to 1.5 °C during summer, 1.75 °C in the middle seasons and 2.0 °C during winter. The thermal comfort range was allowed to vary across seasons to take account of the fact that occupants change their clothing insulation as a function of the outdoor conditions and as they adapt to the climatic variations. This assumption is likely to result in a more conservative estimation of CCP and CCP_h in winter.

To calculate the CCP_h index it was also necessary to make an assumption about the behaviour of the indoor humidity ratio. While the building structure stores and releases sensible heat throughout the day, this does not occur with humidity to the same extent. Assuming that the HVAC systems of most buildings must control their internal humidity level, a relative humidity of 60%, 50% and 40% was used for summer, shoulder seasons, and winter, respectively, as defined in ISO 7730 Standard [43]. Therefore, a seasonally constant indoor humidity ratio was

used to estimate the indoor enthalpy; for example, in summer a value of 0.0115 kg/kg dry air, equivalent to a relative humidity of 60 % at 24.5 °C, was used.

The resulting indoor and outdoor temperatures and enthalpies for one exemplar day, the 23rd of October, in Sydney are presented in Figure 3. This figure shows that Ventilative Cooling could not have been used between 19:00 and 00:00 (highlighted in red in the figure), since the enthalpy outdoors was higher than the enthalpy indoors. This is despite the fact that the temperature outdoors was lower than the indoor temperature by more than the threshold temperature (3 °C) during that period.

Figure 3 Indoor and outdoor temperatures and enthalpies during four consecutive days in October 2018 in Sydney. Grey shaded areas indicate when both the CCP and CCP_h indexes consider Ventilative Cooling feasible, while the red shaded area shows when Ventilative Cooling would have been feasible only for the CCP index.

2.4 Practical Significance of the Enthalpy-Based Climatic Cooling Potential (CCP_h)

The significance of the Enthalpy-Based Climatic Cooling Potential is very similar to the Climatic Cooling Potential, however the inclusion of humidity allows the CCP_h index to provide information on both the sensible and latent cooling constraints and potential of Ventilative Cooling.

The CCP_h index can be used to determine how much cooling energy can be offset by a Ventilative Cooling process when this is active. The CCP_h, represents the cumulative energy in KJ per kg of air that can be offset by the enthalpy difference. The mass flow rate, in kg/hour can be defined as $\dot{m} = ACH \cdot V \cdot \rho$. The total energy Q that the Ventilative Cooling can provide in a day is therefore calculated as in Eq. 6.

$$Q = \dot{m} \cdot CCP_h \quad (6)$$

Utilising the enthalpy instead of the temperature in the index calculation not only takes into account the latent heat in the mass and energy transfer, but it also allows the introduction of further constraints that do not allow Ventilative Cooling to operate when it is not appropriate to do so from an energy perspective.

An example was provided in Figure 3. In this case, using the proposed CCP_h index, the Ventilative Cooling system was employed only in those instances where both enthalpy and temperature outdoors were lower than indoors.

The concept of exchanging air with the outdoors only when it is beneficial for the building from the enthalpy point of view can be extended to real time control of Ventilative Cooling equipment too. This would require a relatively small additional layer of complexity to the control system, including measurement of the indoor and outdoor humidity, calculation of the indoor and outdoor enthalpy and the inclusion of an additional constraint in the control system.

3 Results and Discussion

3.1 Data Validation and methods comparison

To ensure that the BOM weather dataset utilised in this study correctly represented the Australian climate and the relative values of CCP and CCP_h , a direct comparison was made between the BOM observations dataset and the RMY climate files for Australian state capital cities. The results are presented in Figure 4a and Figure 4b. To facilitate comparison with the results presented in [19], the CCP and CCP_h are also reported here for night-time ventilation only, in Figure 4c. For example, comparison of Figure 4c with the result presented for Europe in [19] indicate that Canberra's climate is similar to Zurich in terms of CCP index, whereas Adelaide, Sydney and Perth are more similar to Lisbon. The cumulative yearly values of the indices are also summarised in Table 1.

Table 1 Comparison between the mean daily CCP_h and CCP over the course of year for the Australian capital cities using the BOM dataset (all-day), RMY dataset (all-day) and BOM dataset (night-time only).

Location	All-day				Night-time	
	BOM		RMY		BOM	
	CCP_h (kJ·h/kg)	CCP (K·h)	CCP_h (kJ·h /kg)	CCP (K·h)	CCP_h (kJ·h/kg)	CCP (K·h)
Adelaide Airport	260	151	274	164	163	99
Brisbane	99	76	103	82	77	62
Canberra	384	226	411	253	245	154
Darwin Airport	1	1	4	2	1	1
Hobart Airport	417	238	431	258	244	147
Melbourne Airport	336	204	356	229	206	133
Perth Metro	181	130	202	137	126	96
Sydney (Observatory Hill)	183	108	182	132	114	72

Figure 4 Monthly average CCP_h and CCP for the Australian capital cities, a) BOM dataset, b) RMY dataset and c) BOM dataset (only night-time)

The indices calculated using the two data sources are seen to be similar, with the greatest relative differences being in climates with low climatic cooling potential in terms of CCP and

CCP_h. This is to be expected as the climatic variations between years will have a relatively larger impact on climates with a lower cooling potential.

The CCP and CCP_h results can be compared if the CCP was transformed to a cumulated daily sensible energy from the current cumulated temperature difference. This can be achieved by multiplying the CCP index by the air heat capacity (i.e. approximately 1.004), which makes the results almost directly comparable.

In some of the cases shown in Figure 4 the humidity has a significant effect, not only on the absolute value of the Climatic Cooling Potential, but also on how it is distributed over the course of the year. The results show that the CCP_h would generally predict a higher potential in winter (the outside air is cold, but also dry in terms of absolute humidity because of the air temperature), but lower in summer in humid climates (e.g. Brisbane, Sydney).

For example, in Brisbane, which features a hot and humid summer, the CCP_h index would indicate that the climate is mostly not suitable for Ventilative Cooling for the seven months between October to April, where only two of these months present a non-zero CCP_h. By contrast, the CCP index is close to zero for only three months (i.e. January, February and March).

Furthermore, different climates, and therefore different temperatures and humidity levels, will influence the two indices in different ways. This can be observed by comparing the CCP and CCP_h indexes for Sydney, Perth and Adelaide. The three cities appear similar in terms of CCP, but much greater difference can be observed in the CCP_h. For example, according to the CCP_h Sydney has a lower potential in summer compared to Perth, but higher in the winter months, whereas Adelaide generally has greater potential over the whole year.

3.2 Spatial and Temporal Analysis

The CCP index can be evaluated in more detail by undertaking a temporal analysis of the datasets for a specific location, an example of which is shown for Sydney in Figure 5. This analysis enables more specific identification of the temporal suitability of a Ventilative Cooling technology, and a simpler quantification of the benefits.

Figure 5 shows that Sydney has an acceptable Climatic Cooling Potential during the entire year. The CCP_h and CCP follow an overall similar trend, but CCP_h shows much greater potential during winter months relative to summer months. The daily mean value of the CCP index is approximately 50 K·h during summer and approximately 200 K·h in winter, while the daily CCP_h is approximately 50 KJ·h/kg in summer and approximately 450 KJ·h/kg in winter. The CCP_h winter-to-summer ratio is more than double than the CCP winter-to-summer ratio. This is primarily due to the summer humidity levels in Sydney, which do not allow as much cooling as the CCP would suggest.

Figure 5: Temporal analysis of the Climatic Cooling Potential (CCP and CCP_h) in Sydney using a 'violin' plot to represent the distribution of the daily results.

A spatial analysis of the indices plotted on a map of Australia provides a useful overview of the climatic potential for Ventilative Cooling in Australia for a particular time of the year.

The mean values CCP_h for Australia in February (typically the hottest month) is provided in Figure 6. As expected, a clear progression is observed from south to north, in an opposite direction to the results collected in Europe [19]. A gradient can also be seen moving inland from the coast, due to the moderating effect on temperatures of the ocean.

Figure 6: Spatial analysis of the CCP_h index in Australia in February 2018. Location of capital cities is indicated, and can be identified with reference to Figure 1.

Most of Australia's highly populated cities are on the coast and below the 30th parallel south (i.e. Sydney, Melbourne, Canberra, Adelaide and Perth), and can be seen to have a climate suitable for the application of Ventilative Cooling technologies even in summer (i.e. Climatic Cooling Potential of around 50-150 kJ·h/kg or K·h per day). The rest of Australia (other locations above 30 °S) is mostly unsuitable for Ventilative Cooling in summer.

A spatiotemporal analysis of the indices is presented in Figure 7, showing the monthly variation of the CCP and CCP_h across Australia. During winter and middle seasons the area in which Ventilative Cooling can be applied expands to include the majority of Australia. Note that the colour scale of Figure 7 is different from the one of Figure 6, in order to better represent changes in the index throughout the year. Only the north of Australia remains unsuitable for Ventilative Cooling year round, since the tropical climate remains too hot and humid. This can also be seen in Figure 4, where the CCP and CCP_h are equal to zero in Darwin for every month.

The results presented in Figure 7 are particularly relevant to commercial buildings, which in most of the capital cities utilise more energy for cooling than for heating due to large solar gains (transparent façades) and high internal loads. For these buildings the Australian climate represents a good opportunity for decreasing or eliminating cooling load from the air conditioning system.

There is an expected correlation between the Climatic Cooling Potential evolution over the year, shown in Figure 7, and the Köppen-Geiger climate classification presented in Figure 1. During the summer and middle season months (October to April), the areas with higher Climatic Cooling Potential are generally the classified as Cs or Cf, whereas in winter this area extends to the Bs and Bw regions. The importance of latitude in determining Climatic Cooling Potential is clearly visible between May and September. While the Köppen-Geiger classification seems to be able to give a qualitative indication of the possibility for the climate to provide cooling, it would be inaccurate at quantifying the CCP and CCP_h indexes as it equally classifies areas with different average temperatures, and therefore different Climatic Cooling Potential, such as Brisbane, Sydney and Hobart.

a)

b)

Figure 7: Spatiotemporal analysis of the a) Climatic Cooling Potential and b) Enthalpy Climatic Cooling Potential in Australia.

4 Conclusion

In this study, a well-established method to determine the possibility to utilise Ventilative Cooling technologies, the Climatic Cooling Potential (CCP), has been extended to incorporate humidity and a new index, the Enthalpy Climatic Cooling Potential (CCP_h), has been formulated.

The CCP and CCP_h indices were calculated to determine the suitability of Ventilative Cooling technologies for different regions of Australia. A temporal, spatial, and spatiotemporal analysis of the Australian climatic cooling potential were undertaken for both the CCP and CCP_h indices.

The temporal analysis of the CCP and CCP_h indices showed that employing the difference in air enthalpy between the indoor and the outdoor can lead to different conclusions in terms of the potential benefits of Ventilative Cooling technologies over the year. The CCP_h index indicates that in more humid climates the energy benefits that the climate can provide are significantly reduced in summer in relation to winter. This is to be expected since the CCP index only evaluates sensible heat transfer. Furthermore, the CCP index tends to underestimate the potential during winter compared to the CCP_h index, since the colder outdoor air is also generally drier.

The spatial results showed that most of the capital cities in Australia would benefit from the implementation of Ventilative Cooling technologies to varying degrees depending on the season and location. The Ventilative Cooling potential over summer was found to be relatively limited, and generally only applicable to the cities with a latitude greater than 30°S. The potential for Ventilative Cooling extended to the majority of Australia during the shoulder seasons and winter. The only regions found to be unsuitable for utilisation of Ventilative

Cooling to reduce building cooling energy consumption were the tropical regions in the north of Australia.

The CCP_h index can be used to rapidly obtain an indication of the potential for Ventilative Cooling in a given climate, potentially being of benefit during the early design phase of a building. It adds a small layer of complexity to the CCP index, which is valid if only sensible heat transfer is to be considered, requiring humidity data as well for its calculation.

Full building simulations should still be performed at the later design stages to properly estimate the beneficial effects of a Ventilative Cooling technology, taking into account building construction, operational services and systems, and design specifications.

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