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Summer discomfort reduction by direct evaporative cooling in Southern Mediterranean areas

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Abstract

The present study analyses the effect of direct evaporative cooling (DEC) in reducing the number of discomfort hours in the area of Southern Europe and the Mediterranean. A total of 20 urban locations were selected in order to cover different climate conditions in the chosen area. Cooling degree hours and virtual climatic discomfort hours were calculated for the entire set of locations. Furthermore, the analysis is based on a sample building simulated in EnergyPlus for every location considering both a baseline (free running) and a direct evaporative cooling case. Night ventilation was also simulated in order to compare this technique with DEC. The chosen DEC model is the direct CelDekPad, a single stage evaporative cooler compatible with EnergyPlus. A psychrometric analysis was carried out and comfort boundaries identified for helping designers in considering DEC and night ventilation suitability from the early design phases (e.g. building programming).

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Keywords:

1. Introduction

The primary energy consumption of the building sector in Europe, as in most industrialised countries, is about 40% of the total [1] or even more according to recent research studies [2, 3]. The main contribution is related to energy demand for cooling and heating, hot water production, cooking, lighting and other appliances, with half of it occurring in residential buildings. Indoor temperature and humidity control for heating and cooling represents the highest cause of energy consumption in buildings, with energy demand for cooling constantly increasing in both industrialized and growing countries as demonstrated by trends in the air conditioning market showing a growth of

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70% between 2010 and 2015 [4]. This trend has a strong impact on the electrical energy consumption in many countries, increasing peak demand, energy costs, and GHG emissions due to the high emission factor of electricity [5]. The application of passive cooling systems, and, particularly DEC, could represent an alternative solution, hence contributing to the reduction of global warming as set by the agreement reached among 195 countries at the recent COP21 Conference in Paris.

1.1. Structure

This paper focuses on an evaluation of the potential of direct evaporative cooling technologies (DEC) for reducing the amount of discomfort hours in the southern Europe and the Mediterranean region, considering a sample of 20 urban locations which are representative of the different climatic characteristics of this territory. The research deals with an extended summer period that was fixed for this study from May 1st to October 31st for including different durations of the cooling season in the selected locations. The study firstly analyses the climate-dependent cooling demand by calculating the cooling degree hours (CDH) of each location and the number of “virtual” climatic discomfort hours based on the hourly Typical Meteorological Year – TMY – data provided by the EnergyPlus climate database. Secondly, a sample-building unit was simulated in EnergyPlus in order to calculate the number of discomfort hours in the extended summer period for each location. Dynamic simulations were carried out considering different cases (“free running”, “active with DEC”, “free running with night ventilation”, and “active with DEC and night ventilation”) as described in the following paragraphs. A comfort model developed by ASHRAE and based on both temperature and relative humidity is considered. The calculation of the number of discomfort hours is used to analyse the applicability of DEC and night ventilation (NV) in the chosen set of locations for developing new maps of applicability. Furthermore, a psychrometric analysis was carried out (see par. 4) in order to identify comfort boundaries of DEC applicability. A new correlation between expected indoor comfort and outdoor wet bulb temperature (WBT) is presented, defining an outdoor comfort line – when mechanical comfort model is used – of direct evaporative cooling in treating inlet air in buildings.

2. Sample locations and climatic analyses

The Mediterranean area is characterized by the homonym climate, even if southern locations are classified as BWh (cold desert climate) in the Köppen-Geiger classification (see Table 1). The map presented in Fig. 1 shows the climate classification of the chosen set of locations based on the TMY files used.

Fig. 1. Köppen-Geiger classification of the chosen set of locations.

Table 1. Köppen-Geiger classes included in this study.

Climate class	Climate name	Notes
BSh	Hot semi-arid climate	Hot summer and mild to warm winter
BSk	Cold Steppe	Semi-arid dry climate
BWh	Cold Desert	Hot dry summer and cold dry winter
Cfa	Temperate climate	Hot summer and cool quite temperate winter
Csa	Mediterranean Climate	Mediterranean climate with dry hot summer
Dfb	Warm summer continental	Continental climate with humid warm summer and cold winter

For each location, the corresponding hourly TMY provided by EnergyPlus was used for calculating the climatic cooling demand expressed by the Cooling Degree Hour index (CDH). The set point temperature was set to 26°C, according to similar analyses reported in literature [6, 7, 8], and the resulting expression for calculating the CDH is reported in eq. 1. The CDH was preferred to the Cooling Degree Day index (CDD), because of the extended summer period.

$$CDH_{set\_temp.} = \sum_{h=1}^{n} \Delta\theta_h \tag{1}$$

Where $\Delta\theta_h$ is equal to 0 if the average hourly outdoor temperature is below the set point (26°C), and equal to (DBT – set point temp) when it is above this value. The summation is performed for all the hours in the considered period. Fig. 2 shows the CDH_{26} values for each location. Four localities present a CDH_{26} that surpasses 10 000 even if only one case (Eilat) counts a cooling degree hour index greater than 22 000.

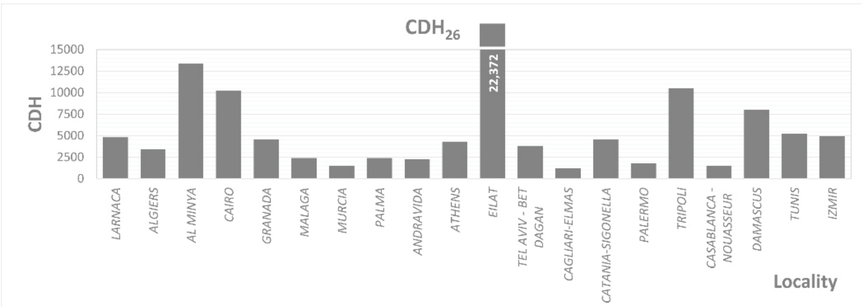

Fig. 2. Cooling degree hours of each location referred to a comfort set-point temperature of 26°C.

Furthermore, the hourly climatic cooling demand intensity, i.e., the frequency distribution of hours by classes of the value (DBT – 26 °C), was analysed for four cities, representing the main different climate zones distributed along the Mediterranean basin (Malaga, Csa; Catania, Cfa; Eilat, Bsh; Damascus, Bsk) as shown in Fig. 3. In this figure, a balance between percentage of hours with (when $\Delta\theta_h > 0$) and without cooling need is also shown by pie diagrams, which give a straightforward representation of the annual climate-dependent cooling need through the CDH_{26} index. Eilat, for example, shows a very high cooling demand that is attributable to hours in which a high and very high difference in temperature is required. At the opposite end in the case of Malaga, the lower CDH_{26} is principally due to a large amount of hours in which the "virtual" required ΔT is between 0 to 3°C.

The expected DEC applicability in the considered locations can be estimated by adapting a methodology presented in the literature [6,7,9] and based on average seasonal values; other methods, based on hourly analyses, are described in other sources [8,10,11]. Other studies are [12,13,14]. Whichever method is used, the applicability/potential of a DEC system in a given location can be assessed by two parameters: the average wet bulb depression (WBD) and the average difference between 26°C and the WBT when cooling is needed. Classes of DEC applicability/potential can be defined by setting intervals of these parameters as shown in Table 2 and crossing them in a qualitative evaluation matrix (null, VL – very low, L – low, M –medium, H – high, VH – very high applicability/potential) as shown in Table 3. Based on this matrix, a classification of the DEC applicability/potential of the selected locations is represented in Fig. 4, showing that the majority of locations belongs to the H or VH class. The usefulness and reliability of this classification was further investigated by means of energy simulations on a building model, by which the above described cooling need in terms of discomfort hours can be converted in energy need. This was done and it is described in the following paragraph. To further improve this approach, an assessment on a wider set of locations is under development.

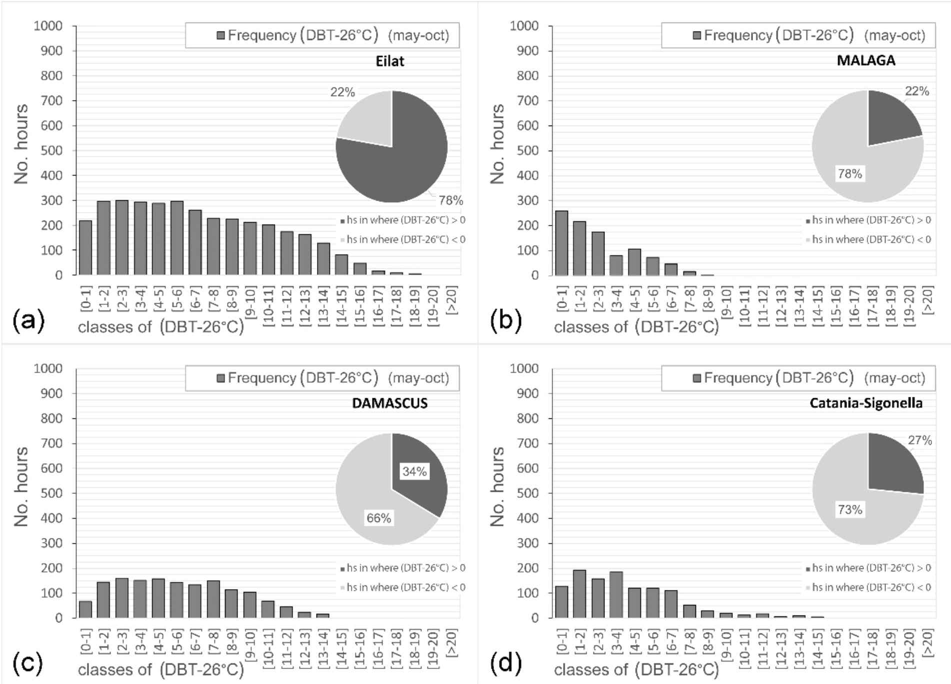

Fig. 3. Frequency distribution of hours by intensity of cooling demand and relevant percentage of total hours in (a) Eilat (ISR), (b) Malaga (ESP), (c) Damascus (SYR) and (d) Catania (ITA).

Table 2. Class boundaries.

Class name	Boundaries (av.WBD)	Boundaries (av. 26-WBT)
cl. 0	av. WBD ≤ 2.5	av. 26-WBT ≤ 3.1
cl. 1	2.5 < av. WBD ≤ 5	3.1 < av. 26-WBT ≤ 5.5
cl. 2	5 < av. WBD ≤ 7.2	5.5 < av. 26-WBT ≤ 7.9
cl. 3	7.2 < av. WBD ≤ 9.5	7.9 < av. 26-WBT ≤ 10.2
cl. 4	av. WBD > 9.5	av. 26-WBT > 10.2

Table 3.Classification of DEC potential (VH – very high; H – high; M – Medium; L – Low; VL – Very Low; Null).

Class name	av. 26-WBT classes				
av. WBD classes	cl. 4	cl. 3	cl. 2	cl. 1	cl. 0
cl. 4	VH	VH	VH	H	not sufficient
cl. 3	H	H	M	M	not sufficient
cl. 2	M	L	L	L	not sufficient
cl. 1	VL	VL	VL	VL	not sufficient
cl. 0	Null	Null	Null	Null	Null

Fig. 4. Classification of DEC applicability/potential of the considered set of locations.

3. Dynamic energy simulation

A series of dynamic energy simulations was carried out on a sample office building unit for every location applying the following indoor climate control configurations:

- Case A: Baseline – free running
- Case B: Direct evaporative cooling (CelDekPad)
- Case C: Night ventilation cooling
- Case D: Night ventilation cooling and DEC

Each case is described in detail in Sec. 3.1 below. The direct evaporative cooling was simulated by using the direct CelDekPad model of EnergyPlus. This model simulates a single-stage evaporative cooling system based on a rigid evaporative pad with water recirculation from a collecting basin [15]. The adiabatic saturation is simulated and the outlet air is a function of the percentage of covering of the WBD. This is simulated according to the following expression, already presented in [16] and validated among others in [17]:

$$\theta_{DBT-outlet\_air} = \theta_{DBT-supply\_air} - \varepsilon_{WBD} \cdot \left(\theta_{DBT-supply\_air} - \theta_{WBT-supply\_air}\right) \tag{2}$$

Where the outlet air is the air leaving the direct CelDekPad and the supply air is the inlet airflow (external air). The ε_{WBD} is the saturation efficiency, which is calculated by the model. The direct pad area was set to 1 m^2, while the depth of the evaporative pad was 0.20 m. The design supply airflow rate was 0.75 m^3/s.

3.1. Model definition

The chosen sample building unit is composed of a two-story office building unit, part of a larger multi-storey building. Each story has two office rooms of about 88 m^2 of gross floor area each, and a corridor of about 24 m^2. The space used for simulation is the office facing South in the upper story of the unit. The chosen space has exposed roof and an external wall in the South-oriented façade, which has a gross area of 35 m^2. The North partition is adjacent to the corridor (same temperature), while the other walls and the floor are considered as adiabatic. No internal loads are considered for this paper considering a very conservative approach because the comparison with climatic applicability classes, even if on going research is analysing the effect of both occupants and internal loads. The external wall has a window of 9.87 m^2 of gross area and horizontal shading devices (overhang), while the net room height is 3 m. The infiltration rate is fixed to 1.5 ACH (day and night) in order to indirectly consider possible openings due to people, typical existing building conditions, and the need for high infiltration due to the fact that evaporative cooling does not work well in tightly sealed buildings because the indoor humidity gets too high. For the night ventilation cooling case, an air flow of 6 ACH is simulated during night (from June to October – 20:00 to 7:00), while the infiltration rate is only considered during daytime (1.5 ACH). The analyses made use of a comfort model developed by ASHRAE 55-1992, based on both temperature and relative humidity values as illustrated in Fig. 5 (b).

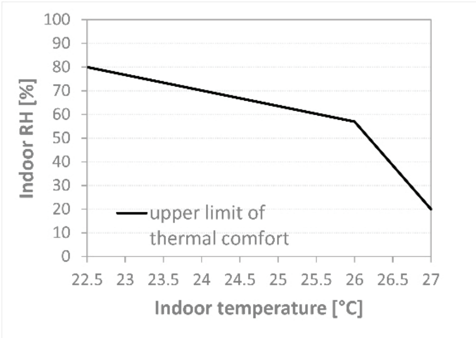

Fig. 5. the ASHRAE 55-1992 comfort model used in the analysis.

3.2. Simulation results

Amid simulations' results, two sets of data are sorted out in order to show the effectiveness of direct evaporative cooling. The first set is related to the hourly variation of air temperature (dry and wet bulb) and relative humidity, both outdoor and indoor, for cases A (free running) and B (evaporative cooling), in the 4 locations shown in Fig. 3. The second is related to the amount of discomfort hours for all 4 cases in all 20 selected locations.

3.2.1. Indoor climate variables

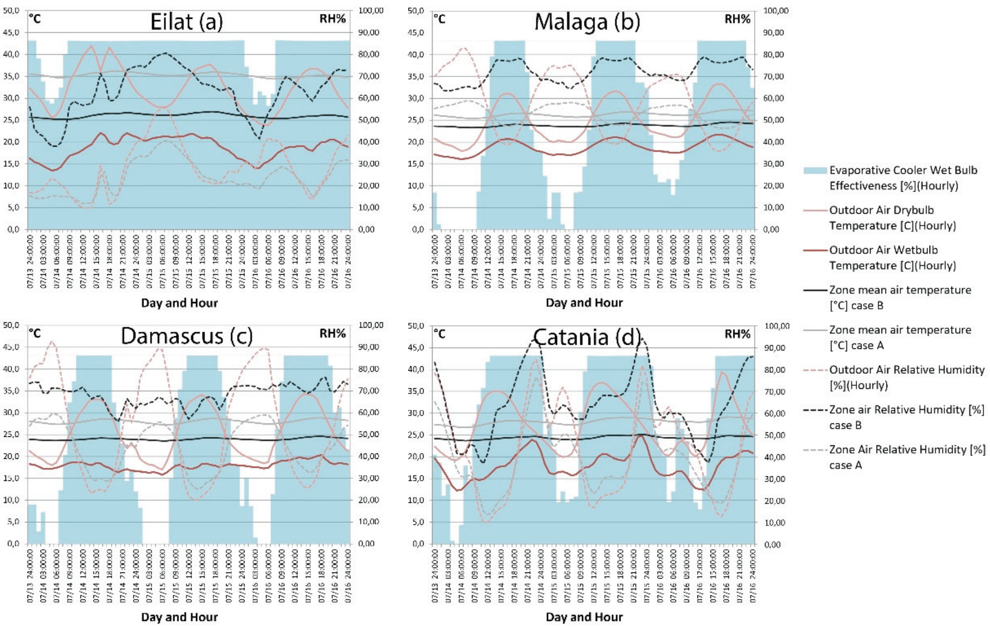

Fig. 6. Trend of air temperature and relative humidity values based on dynamic simulations, for a 3-day sample in (a) Eilat (ISR), (b) Malaga (ESP), (c) Damascus (SYR) and (d) Catania (ITA).

The first set of data is represented in Fig. 6, where diagrams show a decrease of indoor air temperature from the baseline (case A) due to DEC (case B) proportional to the cooling need, i.e., in average, from a few degree in Malaga to around 5 degree in Catania and Damascus, up to 10 degrees in Eilat. The indoor relative humidity follows the outdoor trend in two locations, by increasing its value of an amount dependent on the baseline level (high jump in the very dry Eilat, much lower increase in the more humid Catania); in the other two locations, Damascus and Malaga, the indoor humidity trend appears to be smoothing out the sinusoidal daily trend of outdoor RH.

3.2.2. Comfort and discomfort hours

The amount of discomfort hours for cases A-B-C-D in all considered locations, within the extended summer period of 4416 hours, is shown in. Fig. 7. The reduction in the amount of discomfort hours due to DEC application (case B) with respect to the baseline (case A) varies by location: Eilat, 50%; Damascus, 45%; Al Minya, 24%; Athens, 17%; Granada, 17%; Izmir, 17%; Catania, 14%; Cairo, 14%. If alternative applications of night ventilation (case C) and DEC (case B) are compared, three different patterns of behaviours are present. In a first group of locations, DEC and NV have a similar effect (Larnaca, Malaga, Murcia, Cagliari, Catania, Palermo, Tunis, Izmir), while in a second group NV is a more suitable technology for reducing the discomfort hours than DEC (Algiers, Palma, Andravida, Tel Aviv, Casablanca). In other locations, the effect of NV is lower than DEC (Al Minya, Cairo, Granada, Athens, Eilat, Tripoli, Damascus). The effect of a combination of NV and DEC (Case D) in reducing the amount of discomfort hours with respect to the baseline is always the highest amid the three configurations, except in Eilat, where case B (only DEC) is slightly better than case D due to the extreme ambient conditions of high DBT and low RH, which makes NV a less effective solution than DEC, even if direct evaporative cooling can only halve the number of discomfort hours.

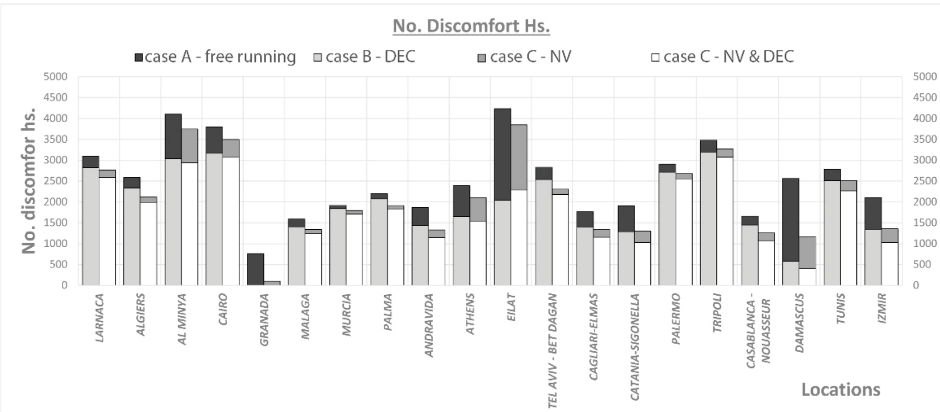

Fig. 7. Total amount of discomfort hours in summer (May 1st- October 31st) in all considered locations for different cases.

A map classification of the balance between comfort and discomfort hours for the simulated building model cases in the 20 selected locations is represented in Fig. 8, which includes separate maps for each of the configuration cases.

The pie charts show in black the percentage of discomfort hours and in white the comfort hours. Through these maps, it is possible to compare both the percentage of discomfort hours in the 20 locations for the baseline case and, in each location, the effectiveness in reducing the discomfort hours with respect to the baseline, i.e., the percentage of comfort hours, related to the application of DEC and NV techniques, separately (case B and C, respectively) and in combination (case D). According to this map, it is clear that DEC can effectively reduce the number of discomfort hours in several of the considered locations, even if in some cases the amount of residual discomfort is quite high. It is evident that night ventilation can provide a significant reduction in the number of discomfort hours in several locations, as mentioned for Fig. 7. When night ventilation is taken into account, the number of discomfort hours converted into comfort by using DEC is further evidenced: see for example the percentage for Eilat (-35%), Al Minya (-18%), Damascus (-17%), Athens (-13%), Cairo (-10%), Izmir (-8%), and Catania (-6%). If the number of discomfort hours turned into comfort is calculated between Case A and Case D, these percentages are respectively higher for Eilat (-44%), Al Minya (-26%), Damascus (-49%), Athens (-19%), Cairo (-17%), Izmir (-24%), and Catania (-20%). The differences between these two data points can help define the effectiveness of DEC when NV is used. Results of NV applicability focused on both mechanical and adaptive comfort approaches (sensible cooling) are reported in [10,18,19].

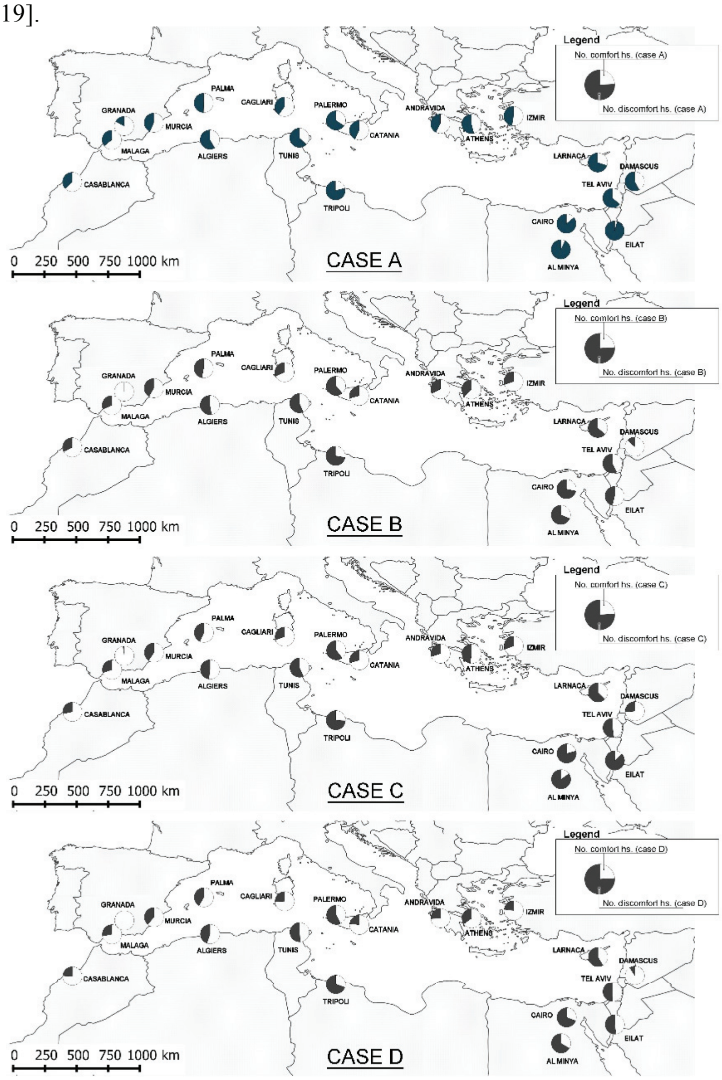

Fig. 8. Distribution of comfort and discomfort hours for each case.

4. Comfort boundaries

Simulated results were used for underlining a possible correlation between external air conditions and indoor comfort/discomfort expectations when using DEC techniques. Fig. 9 shows the distribution of discomfort and comfort hours considering different WBT limits for the four selected cities of paragraph 2. This and further analyses show that indoor discomfort when DEC is activated especially occurs when the external air WBT is higher than about 18°C.

The number of climate-dependent discomfort hours was calculated by elaborating the hourly TMY data of the 20 locations using a WBT comfort limit of 18°C. Results show that, when DEC is activated, indoor discomfort conditions are present if external air WBT is higher than about 18°C. By correlating the amount (percentage of total) of discomfort hours in the simulated case B to the number of hours (absolute values) where the external WBT is below 18°C for each location in the extended summer period, a linear fit with negative slope and a very high R^2 was found as shown in Fig. 10 (a). This supports the use the WBT limit of 18°C as a general rule of thumb for defining the number of hours where discomfort is expected if DEC is used in buildings.

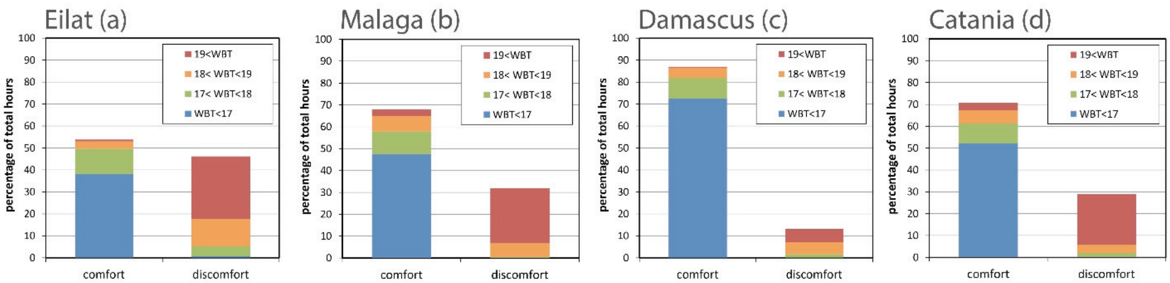

Fig. 9. Percentage of comfort and discomfort hours according to a WBT limit set to 18 °C for (a) Eilat (ISR), (b) Malaga (ESP), (c) Damascus (SYR) and (d) Catania (ITA).

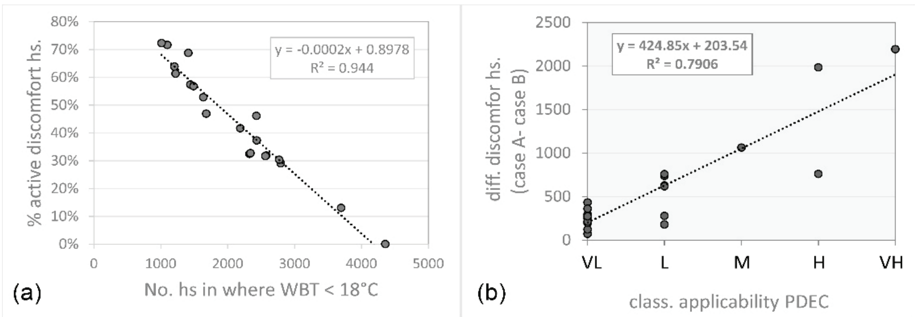

Fig. 10. (a) Percentage of discomfort hours in Case B compared to the number of hours where external WBT is below 18°C for each locality (extended summer period); (b) Comparison between the absolute number of discomfort hours of Case A turned into comfort in Case B and the class of DEC applicability for each location.

Finally, the number of discomfort hours in Case A turned into comfort in Case B was correlated to the classes of climatic applicability of DEC as calculated in Sec. 2. Fig. 10 (b) illustrates that these two data are correlated, even if further analysis (under development) is needed. Ongoing research will consider a larger set of locations and an hourly climatic analysis, based on both mechanical and adaptive comfort models.

5. Limitations

This study is related to the considered TMY source. Difference sources, especially the more recent ones, can modify the results, as demonstrated in a previous study [20]. Furthermore, this research not considers the effect of climate changes on the cooling demand, which is demonstrated to increase in future [21,22,23].

6. Conclusions

This paper presents the first results of a research study on the expected reduction of discomfort hours with respect to a thermally free-floating baseline building in an extended summer period when direct evaporative cooling and night ventilation are used in Mediterranean region. Based on these preliminary results, it is possible to conclude that:

- evaporative cooling can reduce the amount of discomfort hours significantly, especially in a set of hot dry locations;
- night ventilation can significantly reduce the discomfort hours, and in several locations can reach results similar to those expected from DEC (as illustrated in Sec. 3.2.2);
- the combined use of DEC and NV performs better than a separate application of the two techniques, except in very hot and dry locations;
- DEC-NV applicability/potentiality maps can help designers in identifying, even from the initial phases of the building's design, possible passive solutions for reducing indoor discomfort according to local conditions;
- a rule of thumb for the applicability of DEC has been developed, based on the proportion of hours in which ambient wet-bulb temperature is below 18°C;
- the simplified method for estimating DEC applicability according to TMY followed a similar trend than simulation results.

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