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Climatic cooling potential and building cooling demand savings: High resolution spatiotemporal analysis of direct ventilation and evaporative cooling for the Iberian Peninsula

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ABSTRACT

In the present study a new methodology allowing the assessment of building's cooling demand savings by the use of ventilated passive cooling systems is presented in a twofold innovative way. Firstly, using a redefined concept of the climatic cooling potential (CCP), which allows for the direct estimation of savings in building's cooling demand by the use of different passive cooling systems on a large spatio-temporal scale. Secondly, this assessment relies on high resolution climate dataset built using a regional climate model covering the Iberian Peninsula (IP) with a 9 km horizontal spacing and the period between 1989 and 2008. Here, the CCP concept is applied for direct ventilation and evaporative cooling, in such a way that it allows for a comparison with the building monthly cooling demand, providing a direct assessment on the cooling demand savings for any building, for three air flow rates. The results show that CCP is asymmetrically distributed both spatially and temporally within the IP. During the cooling season CCP values are above 1 kWh per m^3 of building and 3 kWh per m^3 of building, for direct ventilation and evaporative cooling, respectively. Evaporative cooling provides a less heterogeneous annual cycle of CCP than direct ventilation, with a relative difference in the south and central part of the Iberian Peninsula superior to 100% during summer. Nonetheless, despite the consistently higher values offered by evaporative cooling, in the coastal regions the relative difference between the two systems drops to less than 10% due to the higher moisture in the air. For the case of a typical office room in the region of Lisbon, in the month of August, the cooling demand savings provided by the use of direct ventilation and evaporative cooling can represent more than 27% and 40% of the cooling demand, respectively.

1. Introduction

1.1. Direct ventilation and evaporative cooling

In 2012 buildings were responsible for nearly 40% of the final energy consumption in Europe, placing the building sector as the biggest energetic consumer, above industry (31%) and transportation (26%) [1]. The rapid increase in electricity demand for air-conditioning associated with the global warming issue, will further boost the primary energy demand for building cooling [2–5]. In the current energy paradigm, this will enhance even more the anthropogenic CO_2 emissions and therefore global warming with its environmentally and societal harmful consequences. The use of renewable energy resources such as the passive cooling systems and their implementation in buildings is mandatory to overcome the current energy paradigm, since they can be an important solution to contribute to minimize buildings cooling loads and thus the fossil fuel dependence. The effectiveness of passive cooling systems has been widely documented through several studies [6–8], however, here we focus only on direct ventilation and evaporative cooling.

Direct ventilation techniques are one of the most used, widely known and simple passive cooling techniques. Whenever there is cooling demand inside a building and the outside temperatures are lower than the building's set point temperature, then the outside air can be brought inside, reducing its temperature and cooling load. The air can flow inside by the use of fans (mechanically

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Nomenclature

CCP	climatic cooling potential (kWh/m^3 of ventilated building)
c	heat capacity of air (kWh/K kg)
ρ	air density (kg/m^3)
v	ventilation flow rate (air changes per hour)
v_{ref}	standard ventilation flow rate (kg/h or air changes per hour)
v_{vnt}	passive cooling system's ventilation flow rate (kg/h or air changes per hour)
T_{bld}	building temperature (°C)
T_{vnt}	passive cooling system output temperature (°C)
T_{set}	building's set point temperature (°C)
T_{ext}	outdoor temperature (°C)
UCP	useful cooling potential (kWh/m^3 of ventilated building)
$Qcool$	building's cooling load (kWh)
$\Delta Qcool$	effective savings (kWh)
η	evaporative cooling system's efficiency
T_{wb}	wet bulb temperature (°C)
ach	air changes per hour (h^{-1})

forced), using the naturally available thermal gradients through openings (natural) or both ways [9]. Direct ventilation is often used during the night and hence commonly referred as night cooling. As recognized in many studies, direct ventilation can be extremely efficient in the reduction of the cooling loads [10–14], though the efficiency is mainly related to the difference between indoor and outdoor temperatures, the air flow rate, the building's thermal mass [11] and cooling demand.

Evaporative cooling is a process where an air flow is forced through a humid membrane or a water surface absorbing some of the water; thus its temperature is reduced through the release of latent heat of vaporization for the change of state of the water molecules from liquid to gaseous. Evaporative cooling can be direct or indirect. In direct evaporative cooling the humidified air is transported directly into the building. Due to the possibility of condensation inside the building, the air can be forced through a membrane allowing for the separation of the water vapour from it. In the case of indirect evaporative cooling, the cooled humidified air is forced into a heat exchanger maintaining its levels of humidity and at the same time decreasing its temperature and lowering the risk of condensation [15]. Evaporative cooling techniques have been proved feasible both from economic and technical stand points through numerous studies [16–19], nevertheless their efficiency can dramatically be reduced in the case of hot humid climates. Nonetheless, it is expected that indirect evaporative cooling systems will represent near 20% of air-conditioned market in buildings over the next 20 years world-wide [20].

1.2. *Climatic cooling potential*

A major obstacle for the implementation of passive cooling systems is related to the necessity of using building thermal simulation or in situ measurements to assess their viability for a particular case, which in both cases are time consuming processes, require expertise and detailed knowledge of building simulation tools which are expensive, making it inaccessible for most of the building designers. In order to address this problem Artman et al. [9] suggested a new integrated index, named Climatic Cooling Potential (CCP), defined as the summation of the products between building and external air temperature difference and the time interval. The CCP gives a measure of the climatic availability for cooling. In the later study, CCP was computed for the night period across Europe using observations for the main cities, allowing an evaluation of the climatic availability for the use of night cooling in those European cities. Nonetheless, this method does not provide information on how effective this potential could be, or which part of the CCP can really be used to lower the building cooling loads. The main shortcomings of the latter study are: firstly, high CCP values may have in fact very low or none utility in case of absente cooling loads; secondly, CCP was only computed for the night period, neglecting some eventual CCP availability during the day. In fact, there are very few studies focused on the potential for passive cooling techniques which are not based on building thermal simulation. Studies based on building thermal simulation provide quantitative information on cooling demand savings by the use of passive cooling systems, but only for specific cases. Other studies, not relying on building thermal simulation, do not provide quantitative information on the effectiveness of the climatic cooling potential and do not relate it to the cooling demand savings [21–23].

Recently, Campaniço et al. [24] were the first to compute a climatic cooling potential for passive cooling systems in a way that it can be directly related to cooling demand savings independent of any building characteristic and without the use of building thermal simulation. In this study, CCP was computed for complete diurnal cycles and then compared to data for building cooling demand, to achieve the cooling demand savings through a simple model. The model was tested against an extensive set of numerical simulation experiments, combining several passive cooling possibilities with different building configurations and meteorological data, resulting in a total of 7776 different cases. The referred model, named Useful Passive Cooling model (UPC) uses as input the building cooling demand for a certain time period (hourly, daily, weekly and monthly values) and then compares it to the CCP for the same time period. It was found that the minimum value between CCP and building cooling demand (UCP) was very close to cooling demand savings. In fact, for a daily accumulation period, due to the typical building's characteristic time constant, UCP is fairly equal to cooling demand savings, with less than 1% error on average. However, good results are also achieved for monthly cooling demand values, with 11% average overestimation of savings for all cases. The results showed unequivocally that the model is a remarkable tool to assess the cooling demand savings in buildings by the use of ventilated passive cooling systems without the use of building's thermal simulation and independently of building properties. Here we redefine and apply the concept of the CCP in an innovative way, which allows for the direct estimation of savings in building's cooling demand by the use of any ventilated passive cooling system for any building and spatiotemporal scale. The methodology and the concepts presented here are applied for the Iberian Peninsula (IP) for evaporative cooling and direct ventilation, nonetheless, they're valid and applicable for any region and ventilated passive cooling system.

1.3. *Climate models*

Global numerical weather prediction models led to the development of an increased number of global climatological datasets like the reanalyses from the European Centre for Medium Range Forecasts (ECMWF) ERA-40 [25] and ERA-Interim [26], from the National Centres for Environmental Prediction [27], and the Twentieth Century Reanalysis Project [28], and others. Simultaneously, a large number of Global Climate Models (GCMs) have been used to build climate change scenarios. This effort has been