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Ventilated Passive Cooling: Climatic Cooling Potential and Cooling Demand Savings

Analysis at a large spatiotemporal scale

Doutoramento em Sistemas Sustentáveis de Energia

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Tese orientada por:
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Documento especialmente elaborado para a obtenção do grau de doutor

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2017

Acknowledgments

I gratefully acknowledge the Ministry of Science, Technology and Higher Education of Portugal for financing this project through the Doctoral grant SFRH / BD / 51329 / 2010. I am thankful to professor Bernard Lachal, Institut des Sciences de l'environnement, University of Geneva, for helpful scientific discussions. I am deeply thankful to my advisors, Professor Pedro Matos Soares and Professor Pierre Hollmuller, for all their support, counselling and friendship both in times when I failed and in those in which I succeeded. I am also thankful to Professor Rita Cardoso for her valuable scientific contributions and suggestions. To my parents and my sister for being ever-supporting and comprehensive no matter what. To all my friends who have closely followed this work, specially to David Ferreira and Maria Pinheiro, for their support and effort in dealing with my frustrations and disappointments during this path. To Nuno Mateus, a colleague and friend, always willing to help. To Pedro Nunes, a supportive colleague who became a dear friend.

Abstract

Buildings are the largest energy consuming sector, above industry and transportation, which places them as one of the major greenhouse gases emitters. Building thermal conditioning represents nearly 50% of their total energy use, mostly heating; however, trends show an increase in air-conditioning adoption for cooling, and, moreover, global warming will probably boost this tendency. The present thesis main goal is to contribute to the characterization of passive cooling systems, and their operating strategies, to reduce buildings energy demand for cooling. For that, first, one has developed a model able to estimate the cooling demand savings based on the climatic cooling potential (CCP) for different ventilated passive cooling systems for buildings. The CCP expresses the cooling load that a passive system can bring to a building as compared with standard ventilation from outdoor. The model was validated with extensive numerical simulations using the thermal simulation tool TRNSYS. For the 7,776 cases simulated, the model was able to reproduce the cooling demand savings with an error below 1% when compared to TRNSYS. In a second phase, using the same model and results from the Weather Research and Forecasting Model (WRF) forced by the global atmospheric reanalysis ERA-Interim, the CCP for direct ventilation and evaporative cooling was computed for the Iberian Peninsula. In a third phase, the WRF forced by the earth system model EC-EARTH for present and future climates allowed to assess the climate change impact on the CCP over Iberia, both for direct ventilation and evaporative cooling. The future simulations follow the Representative Concentration Pathway scenario RCP8.5 from IPCC. The results show that the CCP for both direct ventilation and evaporative cooling is expected to decrease by the end of the century due to increased air temperatures; nevertheless, the future CCP is at most 40% lower than the present CCP. Finally, a comparative analysis between present and future climates cooling degree hours for Iberia was carried out. The results show that, generally, future cooling degree hours increase 2.5 times comparing to the present, which is a higher increase than the corresponding decrease in the CCP.

The model developed, as well as the spatiotemporal datasets derived from it, can be used to estimate the cooling demand savings associated to the use of direct ventilation and evaporative cooling in buildings for Iberia. The proposed methodology can be easily extended for other regions or climates.

Keywords: Passive Cooling; Climatic Cooling Potential; Cooling Demand Savings; Renewable Energy Resources; Iberian Peninsula

Resumo

O sector dos edifícios é o maior consumidor energético, acima da indústria e do transporte. Este facto coloca o sector dos edifícios como um dos maiores responsáveis pela emissão de gases com efeito de estufa. O aquecimento e arrefecimento representa cerca de 50% da energia utilizada dentro dos edifícios, e, embora a maior fração desta energia se deva ao aquecimento do espaço, a tendência tem vindo a mostrar um aumento do número de aparelhos de ar-condicionado. Além disso, a problemática do aquecimento global contribuirá ainda mais para este aumento bem como para o aumento da quantidade de energia despendida no arrefecimento dos espaços dentro dos edifícios. Esta tese tem como principal objetivo contribuir para a caracterização dos sistemas de arrefecimento passivos com recurso a ventilação e das suas estratégias operacionais, possibilitando assim uma redução do consumo energético associado ao arrefecimento dos espaços nos edifícios. Para isso, numa primeira fase deste estudo, desenvolveu-se um modelo baseado no potencial climático de arrefecimento. Este modelo integra temporalmente o produto entre o caudal de ventilação de um dado sistema de arrefecimento passivo e as diferenças entre a temperatura de conforto do edifício durante a época de arrefecimento (aqui definida igual a 26ºC) e a temperatura do ar fornecido pelo sistema de arrefecimento passivo. Do modelo, designado de Potencial Climático de Arrefecimento, ou *Climatic Cooling Potential* (CCP), resulta o potencial de arrefecimento, ou, a quantidade máxima de energia térmica que um dado sistema de arrefecimento passivo sujeito a um determinado caudal de ventilação é capaz de extrair de um edifício num dado intervalo de tempo, em kWh. Os resultados provenientes do modelo CCP são comparados com as necessidades de arrefecimento do edifício num determinado intervalo de tempo, sendo que do valor mínimo entre as necessidades de arrefecimento e o CCP, nesse mesmo intervalo de tempo, resulta o potencial útil de arrefecimento ou *Useful Cooling Potential* (UCP). O UCP representa a quantidade de energia que se poderá poupar no arrefecimento de um edifício fazendo uso de um determinado sistema de arrefecimento passivo. Nesta tese aplicaram-se os modelos suprarreferidos, a diferentes sistemas de arrefecimento passivos com recurso a ventilação, nomeadamente, ventilação direta, tubos enterrados, arrefecimento evaporativo, sistema de desfasamento térmico (*phase shifter*), e combinações entre estes. O modelo do CCP foi aplicado a cada um dos sistemas de arrefecimento passivo para uma base de dados climática horária da região de Genebra,

Suíça, para os anos de 2003 e 2004. Além disso, paralelamente, conduziram-se uma série de simulações através do software de simulação térmica TRNSYS. As simulações via TRNSYS foram conduzidas para a mesma base de dados climática utilizada no modelo do CCP. Estas simulações tiveram em conta a simulação integrada de cada um dos sistemas de arrefecimento passivo em foco, bem como as suas combinações para um edifício típico, onde se fez variar o tipo de isolamento, inércia térmica, ganhos internos, área de envidraçado e proteção solar exterior, resultando num total de 7,776 casos diferentes. Posteriormente, dos dados das necessidades de arrefecimento provenientes das simulações TRNSYS, para os casos em que não foram utilizados sistemas de arrefecimento passivos (casos de referência), e dos dados do modelo CCP, calculou-se o UCP. O UCP foi calculado tendo em conta dados horários, diários, semanais e mensais das necessidades de arrefecimento do edifício, e foi comparado com os resultados provenientes da simulação TRNSYS para cada um destes intervalos de tempo, para cada sistema de arrefecimento passivo e solução construtiva. Desta análise, verificou-se que que os dados das necessidades de arrefecimento para os quais o modelo do UCP produz os resultados da simulação via TRNSYS com menor erro são os dados diários. Nestes casos, o erro médio entre a poupança energética calculada através do TRNSYS e do modelo proposto é inferior a 1% (considerando a totalidade dos 7,776 casos). Nos casos em que se procedeu ao cálculo do UCP baseando-se em dados horários das necessidades de arrefecimento, o valor da poupança energética associada ao uso dos sistemas passivos é subestimado face aos resultados das simulações via TRNSYS. Para os casos em que se procedeu ao cálculo do UCP com base nos dados semanais e mensais das necessidades de arrefecimento, as poupanças via modelo UCP são sobrestimadas face aos resultados das simulações TRNSYS. No entanto, mesmo para o pior dos casos (dados horários das necessidades de arrefecimento), o coeficiente de correlação estatístico (R^2) entre o modelo UCP e as simulações TRNSYS é superior a 0,95. Para o casos em que se utilizaram dados mensais das necessidades de arrefecimento, o valor de R^2 é superior a 0,96. Assim, na primeira fase deste estudo, desenvolveu e validou-se um modelo capaz de estimar as poupanças energéticas associadas ao uso de diferentes sistemas de arrefecimento passivo por ventilação para uso em edifícios. O modelo não recorre a simulação térmica e é “independente das características do edifício”, sendo que para uso do mesmo, são apenas necessários os dados das necessidades de arrefecimento do edifício em causa, sejam estes dados horários, diários, semanais e/ou mensais. Numa segunda fase, face à boa correlação entre o modelo UCP e as simulações TRNSYS, o modelo foi adaptado por forma a que pudesse ser expresso em unidades de energia por volume (kWh/m^3), e dessa forma possibilitar o mapeamento do CCP a uma larga escala espaciotemporal. Nesta fase do estudo, através da adaptação do modelo do CCP e fazendo uso de uma base de dados climática de alta resolução espácio-temporal, foi possível realizar um mapeamento ao nível da Península Ibérica do potencial de arrefecimento passivo possibilitado pelo uso dos sistemas de ventilação direta e arrefecimento evaporativo em edifícios. A base de dados climática utilizada foi criada através do modelo numérico de mesoescala atmosférico para a predição climática *Weather Research and Forecasting* (WRF), forçado pela reanálise ERA-Interim e comtempla um total de 21870 pontos inclusos na Península Ibérica, para os quais existem registos horários das variáveis meteorológicas. Numa terceira e última fase deste estudo, visando o impacto das alterações climáticas no comportamento dos sistemas de ventilação direta e arrefecimento evaporativo, o modelo WRF, forçado pelo modelo do sistema terra EC-EARTH foi comparado face às simulações forçadas pela ERA-Interim, concluindo-se que as simulações forçadas pelo modelo EC-EARTH podem ser utilizadas para simulação do clima futuro. Assim, o modelo EC-EARTH foi utilizado para os climas presente e futuro, permitindo-se avaliar o efeito da mudança climática no potencial de arrefecimento passivo na Península Ibérica para estes sistemas. As simulações de clima futuro do modelo EC-EARTH integram os dados das concentrações de CO_2 do Representative Concentration Pathway scenario 8.5 (RCP8.5) do IPCC. Os resultados mostram que embora exista um decréscimo do potencial de arrefecimento passivo, devido ao aumento das temperaturas no final do século, este decréscimo é no máximo 40%. Por último, e de forma complementar, procedeu-se a uma análise comparativa entre os graus hora de arrefecimento para os climas presente e futuro, mostrando-se que os graus hora de arrefecimento aumentam em cerca de 2,5 vezes face ao presente, o que representa um aumento maior do que o decréscimo que se verifica no potencial de arrefecimento passivo para o clima futuro.

O modelo aqui desenvolvido, bem como as bases de dados que dele derivam, podem ser facilmente utilizados para estimar as poupanças energéticas associadas ao uso dos

sistemas de ventilação direta e arrefecimento evaporativo em edifícios na Península Ibérica. A metodologia aqui proposta pode ser utilizada noutras regiões e climas.

Palavras-chave: Arrefecimento Passivo; Potencial de Arrefecimento Climático; Poupanças Energéticas de Arrefecimento; Recursos Renováveis de Energia; Península Ibérica

Publications list

This doctorate is based in the following original publications, which are reproduced in chapters 2, 3 and 4:

Paper 1:

Hugo Campaniço, Pierre Hollmuller, Pedro M. M. Soares (2014), Assessing energy savings in cooling demand of buildings using passive cooling systems based on ventilation, Applied Energy, Volume 134, Pages 426–438

Paper 2:

Hugo Campaniço, Pedro M. M. Soares, Pierre Hollmuller, Rita M. Cardoso (2016), Climatic cooling potential and building cooling demand savings: High resolution spatiotemporal analysis of direct ventilation and evaporative cooling for the Iberian Peninsula, Renewable Energy Volume 85, Pages 766–776

Paper 3:

Hugo Campaniço, Pedro M. M. Soares, Pierre Hollmuller, Rita M. Cardoso (2017), Impact of climate change on building cooling potential of direct ventilation and evaporative cooling: a high resolution view for the Iberian Peninsula. Submitted to Renewable Energy

1. Table of Contents

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List of abbreviations and nomenclature

ach	(air changes per hour (h^{-1}))
AR	(assessment report)
CCP	(Climatic Cooling Potential)
CDH	(Cooling Degree Hours (Kh)
E.U.	(European Union)
ECMWF	(European Centre for Medium-Range Weather Forecasts)
GCM	(Global Circulation Model)
GHG	(Greenhouse Gases)
HVAC	(Heating Ventilation and Air Conditioned)
IPCC	(International Panel on Climate Change)
RCM	(Regional Climatic Model)
RCP	(Representative Concentration Pathway scenarios)
UCP	(useful cooling potential)
U.S.	(United States)
WRF	(Weather Research and Forecasting)

1. Introduction

Global Warming and its anthropogenic relation, as well as its damaging consequences, are no longer hypothesis, but instead scientific facts. The number of scientific publications related to Climate Change has more than doubled from 2005 to 2010. Between 1970 and 1990, the number of Climate Change related studies published in English was less than a thousand, but at the end of 2012, this number was already over 150 thousand [1]. These studies have shown the irrevocability of the global warming phenomena by anthropogenic actions, caused by emissions of greenhouse gases, especially CO2, and its threatening influence on Earth´s ecosystems as well as society. In fact, the scientific consensus about recent global warming as consequence of human activities is over 97% [2]. In 2012, renewable energies represented less than 12% of the World energy demand. The latter is increasing at an average of 1.40% per year [3] and world population at 1.13% [4]; since Earth is a finite system, it is impossible to endure with this paradigm, thus, the replacement of the non-renewable energy sources is crucial. Besides the finitude of fossil fuels, its use gives origin to most of the anthropogenic greenhouse gases emissions, which impacts on climate and ecosystems. The International Panel on Climate Change (IPCC) latter Assessment Report (AR5) [5] uses four different Representative Concentrations Pathways (RCP) to assess the Climate Change and its consequences due to the anthropogenic greenhouse gases (GHG) emissions. The RCPs are based on population size, economic activity, lifestyle, energy use, land use patterns, technology and climate policy, and vary from a lower GHG emission scenario to a high emission scenario. The AR5 shows a clear relation between the RCP scenarios and the projected temperature change till the end of the century, which is expected to rise in any of the scenarios considered. Even the stringent RCP scenario (RCP2.6) projects a global mean surface temperature increment between 0.3°C and 1.7°C by the end of the century (2081–2100), relatively to 1986–2005. The effect of climate change is believed to imply the occurrence of warmer temperatures, decrease in precipitation levels in mid-latitude and subtropical dry regions and increased precipitation in mid-latitude wet regions, as well as an increase in ocean acidification [5]. These consequences will negatively affect marine and terrestrial species as well as their habitats, food production, heath and economy. The current energy mix is far from being a viable solution to ensure a sustainable future. The implementation of clean and unlimited energy sources is vital and should be done at a large scale, ideally, in a short term.

Buildings are the largest energy consuming sector worldwide, representing nearly 40% of the energy consumption in the E.U. and the U.S., of which over 50% is due to space heating and cooling. [6] Although space heating may represent a bigger ratio then space cooling (~68% of energy demand dedicated to space heating and cooling in U.S. residential and commercial buildings is due to space heating) [7], the warming climate issue will further boost the implementation of air conditioned devices and will increase the number of cooling operating hours in order to maintain comfort levels. Therefore, building space cooling is an important issue concerning global energy demand and climate change. Here emerges the scope of the present thesis, which aims to fill some of the gaps in the existing literature, by contributing to the state of the art knowledge concerning building cooling demand reduction given by ventilated passive cooling systems.

A passive system can be considered as any system that operates or performs a specific function without any or nearly any need for an external source of energy besides the ones which are naturally and "permanently" available [8]. In this sense, a passive cooling system or device is any system or device that can promote heat losses or decrease the heat gains from a certain system, such as a building, without any need for an additional energy source beyond those which are naturally and permanently available. In literature, the Solar and Heat Protection Techniques are considered passive cooling techniques [9], although the application of these techniques does not promote the extraction of heat from inside a building, but they will reduce the amount of heat that is transferred to the building. These techniques are extremely important, once they can drastically reduce the heat gains and therefore decrease the cooling loads; however, they cannot suppress the dependence on cooling devices alone. These techniques can include shading, insulation, radiative cooling, and control of internal heat gains, among others [10]. Other techniques, which promote heat losses, are often referred as heat dissipation techniques. They use low temperature heat sinks/reservoirs to dissipate the excess of heat from the building [11]. The most important heat sinks/reservoirs are the atmosphere, lakes and oceans and the lithosphere [12]. This study will be focused on the heat dissipation techniques, more specifically the following ventilated passive cooling systems; direct ventilation, evaporative cooling, buried pipes, and the thermal phase shifting. A full description and a state of the art review of these systems is available in chapters 2, 3 and 4 of this document.

1.1.Research Questions

The literature concerning passive cooling systems is vast and rich, mostly proving a great potential inherent to the use of such systems, both from energetic and economic points of views. Still, the behavioral analysis of these systems, such as their efficiency on reducing cooling loads in a particular building in a given region, is attached to the use of complex simulation tools. The integration of the passive cooling systems in thermal simulation tools requires expertise and the fundamental knowledge on the passive cooling systems. The latter fact tends to restrict and diminish their implementation. Only a few studies sought to provide ways to overcome this difficulty. In fact, none of the existing literature has focused on proposing a simple but precise evaluation method/model able to predict the cooling demand savings in buildings, associated to the use of ventilated passive cooling systems. Ideally, to overcome these difficulties, such method should be independent of building properties and not require the use of thermal simulation tools. Hence, here rises the first research questions addressed in this thesis:

For the case of passive cooling systems based on ventilation, is it possible to compute a climatic cooling potential as a function of meteorological data, independently of any building properties? If so, how can it be linked to the cooling load of a particular building, for yielding of the associated useful cooling potential?

Development and validation of such a model would constitute a valuable tool for HVAC companies to use and thereby conduct knowledgeable proposals to consumers, involving solutions apart from the conventional ones (i.e. air conditioned devices), which in turn, would have a substantial contribution towards the implementation of passive cooling systems and therefore in reducing the global demand for fossil fuels. Moreover, enhancement of such a model could allow a comprehensive characterization of some passive cooling systems at a large spatiotemporal scale. Therefore, a valuable data set, comprising geographical information regarding cooling demand savings associated to use of a certain passive cooling system in any building, could be established. This leads us to the 2nd research question:

In the case of the Iberian Peninsula, how do the climatic cooling potential of direct ventilation and evaporative cooling behave and compare in present climate?

Even in the case where the aforementioned data set is available, a question still remains. Climate is changing and getting warmer, which will likely affect the contribution of the ventilated passive cooling systems for cooling demand reduction in buildings. Therefore, it is important to assess the effects of climate change in passive cooling systems and the cooling demand reduction that they provide, namely, whether they still worth the investment from an energetic/ecological point of view. This leads to the 3rd and final research question covered by this thesis:

In the case of the Iberian Peninsula, what could be the impact of climate change on the cooling potential of direct ventilation and evaporative cooling?

Summarizing, the purpose of this thesis is to create knowledge related to the use of ventilated passive cooling systems, by introducing innovative and validated methodologies, from which one can easily assess cooling demand reduction in buildings. This will also hopefully contribute to increase the implementation of such systems at a large scale and consequently contribute to a sustainable energetic paradigm, by reducing fossil fuels dependency and hence mitigating GHGs emissions.

1.2. General approach

This section succinctly describes the backbone of the methodology followed in this work, providing an overview over the approach used to tackle the research questions. The detailed methodology, namely its analytic components, is explicit in papers 1, 2 and 3, which contents are reproduced in the chapters bellow.

Building thermal behavior and ventilated passive cooling systems behavior are strongly related to local climate. Therefore, to characterize the ventilation systems, there is the need for detailed climate observations. The literature concerning passive cooling systems is vast, still, only a few studies aimed to the characterization of these systems in terms of their potential at a large spatiotemporal scale, relating it with the cooling demand savings in buildings. Artman et al [13] proposed a climatic index named climatic cooling potential (CCP), and defined it as the summation of products between building and external air temperature-differences and time interval. This index was computed for the case of night time direct ventilation for several locations across Europe, however, no relation between CCP and effective savings was established. Other studies, concerning the potential of passive cooling systems either rely on thermal simulation software [14], or do not establish a relation between the CCP and the cooling demand savings in buildings [15, 16]. To overcome these difficulties, in a first phase of this study (2nd chapter), a methodology linking the CCP potential for several ventilated passive cooling systems and cooling demand savings is established and validated. Then, in chapter 3, the proposed methodology of 2nd chapter is applied to a high-resolution regional climate simulation. These regional climate simulations were performed using the state-of-the-art atmospheric mesoscale numerical weather prediction system WRF (Weather Research and Forecasting) as a regional climate model (RCM) [17]. The WRF simulation presented in chapter 3, for the Iberian Peninsula was forced by the ERA-Interim reanalysis [18]. ERA-Interim is a global atmospheric reanalysis which is continuously updated in real time and its produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) which uses the atmospheric model and data assimilation system Integrated Forecasting System (IFS). The spatial resolution of the data set given by the ERA-Interim reanalysis is approximately 80km for the full globe. The WRF simulation was performed at 9 km resolution and covered the full Iberia. Its results were used and evaluated in diverse studies, such as temporal distributions of Portuguese temperature [19, 20] and Iberian solar resources [21]. The output form de WRF model forced by the ERA-Interim reanalysis, particularly, surface temperature (2m), specific humidity (2m) and surface atmospheric pressure, are used as input in chapter 3 to compute the CCP of direct ventilation and evaporative cooling for the period 1989-2008 with a 9 km (WRF9km) horizontal grid spacing for the full Iberian Peninsula.

To assess the climate change impact on the CCP for direct ventilation and evaporative cooling, in chapter 4, the WRF RCM model was forced by the EC-EARTH GCM. The EC-EARTH is an Earth System Model based on the prediction system of ECMWF, it consists of an atmospheric and an ocean model. The EC-EARTH can be forced by different GHGs concentrations scenarios, and other variables, which result in changes in the atmospheric and ocean circulation models at global and regional scales [22]. The EC-EARTH model´s spatial resolution is approximately 120km, and like ERA-Interim covers the full globe. In a first step, and to evaluate the WRF-EC-EARTH simulation, the CCP for direct ventilation and evaporative cooling given by the WRF-EC-EARTH input for present climate is compared to one given by the WRF-ERA-Interim. Finally, a simulation for future climate using WRF model forced by the EC-EARTH for the period 2070-2100, is used to assess the climate change impact on the CCP. In this latter case, the EC-EARTH model uses the CO2 atmospheric concentration levels as defined by the RCP 8.5 from the IPCC latter Assessment Report AR5 for the period 2070-2100 [5]. The RCP8.5 assumes high population with low energy intensity improvements, which in the long term, leads to high energy demand and GHG emissions. It corresponds to the IPCC scenario with the highest greenhouse gas emissions.

1.3. Contents

In order to meet the research questions presented earlier, the next chapters of the current thesis are composed as follows:

Chapter 2: Here a model attempting to answer the first research question is created and successfully validated over 7776 simulations. This chapter constitutes the first original paper published.

Chapter 3: In this chapter a redefined concept of the Climatic Cooling Potential is proposed and its use for evaporative cooling and direct ventilation over a large spatiotemporal scale is presented, successfully addressing the 2nd research question of this thesis. From this study a second paper was published.

Chapter 4: In order to address the 3rd and final research question of this thesis, chapter 5 focus on the climate change effect on some ventilated passive cooling systems output for Iberia. The contents of this chapter allowed the preparation of a third paper that is presently submitted.

Chapter 5: Is the final chapter of this thesis and where the main conclusions of the present work are drawn.

2. Assessing energy savings in cooling demand of buildings using passive cooling systems based on ventilation

Abstract

The objective of this article is to develop and test a simplified method to compute the savings in building cooling demand by use of passive cooling systems based on ventilation (direct night ventilation, air-soil heat exchangers, controlled thermal phase-shifting, evaporative cooling, as well as possible combinations thereof). The systems are characterized in terms of a climatic cooling potential, independently of any building, which is then compared to the cooling load of a particular building. The method is tested against an extensive numerical simulation campaign, combining diverse passive cooling systems and sizes with diverse constructive and operational modes for an administrative building situated in Geneva. The key point of the simplified method is to choose an appropriate time resolution, for taking into account the building thermal inertia. Although best results are obtained with a daily resolution, good results are also obtained with monthly data, where an overestimation of the passive cooling fraction remains less than 20% in half of the cases. This opens way for using the method for first assessing the potential of these passive cooling techniques on a large spatiotemporal scale, for which integrated building and system simulation becomes prohibitive.

Keywords: passive cooling; climatic cooling potential; useful cooling potential; effective savings

2.1.Introduction

2.1.1. State of the art

In most parts of Europe, electricity demand for air-conditioning of buildings is in rapid increase [23, 24], and will be further boosted by the global warming issue [25, 26]. Mitigation of this demand requires as well adequate architectural and constructive measures (reduction of the solar and internal gains, access to the thermal mass), as development of passive cooling techniques. Such techniques make use of naturally available heat sinks, which are usually closely related to local meteorological variables. The viability of such systems/techniques has been proved in several works, either by the use of simulation tools or in situ measurements [12]. State of the art can be divided in studies of effectiveness, implementation, modelling and prediction of the cooling demand reduction in buildings by the use of the referred passive cooling techniques.

Within this study, we will focus on passive cooling systems which are linked to ventilation, namely direct ventilation, evaporative cooling, buried pipes and phase-shifter. The simplest of the mentioned techniques and certainly the most widely used is direct ventilation. Direct ventilation techniques use the ambient cool air to reduce the building´s inner temperature, therefore the building´s structure is used as a heat sink, allowing the inside air temperature to be reduced. Direct ventilation can be mechanically forced (by fans), natural (by openings and use of thermal gradients) or both natural and mechanic [13]. The use of direct ventilation to cool a building is often used during the night period and is referred as night cooling. The direct ventilation cooling effect on the reduction of cooling loads depends on three main parameters: the difference between indoor and outdoor temperatures (mostly during the night), the air flow rate, and the building´s thermal mass [27]. The effectiveness of night ventilation techniques on the reduction of the cooling loads of a building has been proven in several studies [28-31]. As a second technique, evaporative cooling is a process where the latent heat of vaporization of water is used. Evaporative cooling can be direct or indirect. Direct evaporative cooling is the process where cooled and humidified air is directly brought into the building. This process can have low efficiency in the case of humid climate, where air can be close to its saturation point. In order to improve the cooling efficiency the air is sometimes forced into a membrane that allows separation of the water vapor from the air. The indirect evaporative cooling is a similar process but using a heat exchanger (permeable wall) between the air flow and the cooled air, allowing the air inside a room to cool down without increasing its humidity, therefore decreasing the eventual condensation and the consequent release of heat into the room [32]. The evaporative cooling techniques have been largely studied and its efficiency has been shown both from technical and economical stand points [33-36]. It is expected that the indirect evaporative cooling systems will take up 20% of the air-conditioning market in buildings in the next 20 years in particular for the dry and hot climes [37]. The third technique, namely buried pipes or earth to air heat exchangers, act like a damper for the outside temperatures, so that at times of the day when temperatures are high the outlet air is at a lower temperature. There are several modelling and validation studies of buried pipes systems [38-42], as well as on its economic viability and effectiveness on the reduction of buildings cooling loads [43-45]. Finally, thermal input signal delay or phase shifting is a phenomena first discovered in a study concerning a buried pipes system [46]. The thermal phase-shifting device is a storage device where the storage material is homogeneously distributed within a ventilating duct in order to increase the heat-transfer surface of inlet air, and to decrease the penetration distance to thermal mass. In this way a homogeneous airflow and a good convective exchange are provided, permitting to delay the day/night temperature´s oscillation almost without dampening, and allowing the night cooling peak to be available in the middle of the day [47].

All of preceding systems are linked to the ventilation system of the building (possibly with some thermal storage) so as to activate the available cooling resource and distribute it within the building. As will be mentioned further down, several analytical and numerical models allow computing the achievable cooling temperature of these systems in a particular climatic situation, in function of specific design properties. However, determination of the effective cooling potential for a particular building usually needs further integrated dynamic building simulation, with ventilation from the available cooling source [28, 48].

Despite the extensive literature and numerous validation models on the referred techniques, a model relating the output temperatures from a given passive cooling system and the cooling demand savings in a building has not yet been developed in a way independent of building thermal simulation. Ideally such a model would enable the computation of the cooling demand savings in buildings by the use of the aforementioned passive systems in a simplified and accessible way without the need for detailed knowledge on thermal simulation software and of the building properties. In this regard, Artmann et al [13] proposed a new integrated index named “climatic cooling potential” (CCP), defined as the summation of products between building and external air temperature-differences and time interval, that was computed for several locations across Europe. Their results pointed out that for the Northern Europe there is a very significant potential for passive cooling by night-time ventilation, and that even in some regions of Southern Europe the climatic cooling potential is still significant. Nonetheless, these authors didn’t address the relation between potential and effective savings, not emphasizing that even high CCP may have low utility (if there is no cooling needs then even a high CCP represents zero savings). Furthermore, the CCP was computed regardless of any building properties, such as internal gains, cooling demand, thermal inertia and insulation. Finally, the CCP was computed for night cooling only, neglecting some eventual day time potential that may be useful.

Another study in that direction was developed by Belarbi et al [14]. These authors suggested two approaches in order to evaluate the passive cooling potential. The first one is independent of any building characteristics, and the second is based on thermal simulation of the building. Both methodologies provide helpful information on the viability of the passive cooling techniques, however, the first only characterizes the “effectiveness” of a certain passive cooling system relatively to different climatic zones. The second approach allows a more detailed view, nevertheless, it requires expertise and detailed knowledge on thermal simulation software and of the building properties. A more recent study by V.I. Hanby et al [15] used UK climate projections (UKCP09) to access the wet-bulb depression and the effects of climate change on the performance of evaporative cooling systems. They simulated a simplified single zone building model combined with an evaporative cooling plant. The results provided by simulations showed that the evaporative cooling plant was able to decrease the cooling demand, however this decrease was lower than the one provided by the meteorological evaporative potential. Nevertheless, it was concluded that the evaporative cooling systems are a viable solution for cooling buildings presently and in the context of a changing climate. Although, this study showed a comparison between the potential provided by the weather data and the simulated building, no relation between savings and potential was established. Additionally, the evaporative cooling potential was simulated only for the summer period (taken as April to September) and for the occupation hours (07:00 to 19:00), neglecting some eventual potential, mostly during night, which might be used to take advantage of the building´s thermal inertia decreasing the cooling loads on the day after.

A.T.Nguyen et al [16] presented a method to assess the thermal comfort using passive systems (natural ventilation and passive cooling). This method was applied for the hot humid climate of Vietnam, and it relies on the selection of an appropriate comfort zone on a building psychometric chart, the extraction of data from the chart and printing, and on the analysis and assessment of thermal comfort, heating and cooling potential of passive strategies. It is a helpful tool for a quick assessment of the availability of thermal comfort by way of passive systems. Regardless of the simplicity of the method and its applicability do different climates, the results only express the potential percentage of time within thermal comfort that can be achieved in a certain climate using some passive systems, not relating it with savings in energy demand. Furthermore, in the referred study the method was not validated against simulations or in situ measurements, which raises questions regarding its effectiveness.

2.1.2. Objectives

The main goal of this paper is to develop and test a performance indicator for passive cooling systems based on ventilation. This indicator, to be called climatic cooling potential, should be sufficiently robust to allow the estimation of the potential savings in cooling demand of buildings, without need for integrated building-system simulation. The fundamental outcome of such an indicator is, for ongoing work, to allow the characterization of the diverse cooling techniques on a large geographical area (some hundreds of km) and a large time horizon (some decades, including future climate change scenarios), for which overall building simulation becomes computationally unaffordable, due of the many possible architectural and operational configurations. In this sense, the objective of the climatic cooling potential is not to replace integrated building simulation, which will give finer results, but to allow for rough estimation of the potential of the aforementioned cooling techniques on a large geo-referenced spatial and temporal scale.

For this purpose, we will develop a method which allows: i) to characterize the diverse passive cooling techniques linked to ventilation in a coherent way, independently of any building, in terms of output temperature and associated airflow; ii) in a second step, to evaluate their effective contribution in terms of thermal energy savings for a particular building, as characterized by its cooling demand in absence of passive cooling. In this respect, one of the crucial points is to determine the time step at which the cooling sources (and separately the building cooling demand) have to be characterized. For this sake, the simplified method developed hereafter will be validated against integrated building simulation, for the case of an administrative building located in Geneva, for an important set of passive cooling techniques, as well as a variety of constructive and operational configurations (solar protection, thermal mass and insulation, internal gains).

This paper is organized as follows. In section 2.2 we present the studied cooling passive systems, as well as their physical properties and a brief reference to related analytical models. section 2.3 is devoted to the description of the proposed method, which allows the computation of the climatic cooling potential and the associated cooling demand saving. For the sake of validation, in section 2.4 the method will be compared to integrated building-system simulations. Section 2.5 shows a brief description on the behavior (provided by integrated simulation) of some of the passive systems, followed by the results and validation of the proposed method. Finally, the main conclusions of the present study are presented in section 2.6.

2.2. Passive cooling with ventilation

2.2.1. System description

As an alternative to direct ventilation, for which the available cooling temperature is given by the outdoor condition, we will consider two types of passive cooling systems based on thermal storage of the meteorological day/night oscillation that is carried by ventilation (figure 2.1).

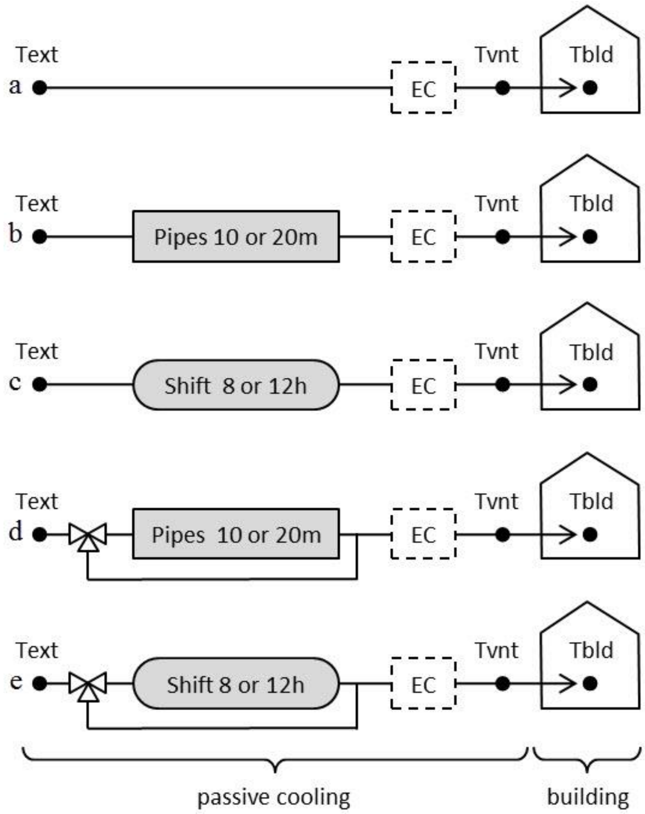

Figure 2.1. Schematic layout of passive cooling systems: (a) direct ventilation, (b-c) buried pipes and thermal phase-shifting, (d-e) buried pipes and thermal phase-shifting, combined with direct ventilation. All systems are considered with or without evaporative cooling (dashed box).

The first concerns air-soil heat exchangers, in which the air passes through an array of pipes buried under or next to the building, for the meteorological day/night oscillation to be dampened by charge/discharge in the soil. Previous work allowed for the analysis of several case studies, as well as for development of well validated numerical and analytical models [38, 39, 46, 47]. As the daily heat wave propagation around the pipes extends on approximately 15-20 cm, latter can be arranged in a compact geometry, with inter-axial distance of approximately 50 cm, immediately under the building, if necessary in multiple layers. Although such systems may in principle also be designed for dampening of the summer/winter oscillation, the associated size (approx. 2 m depth and 4 m inter-axial distance) generally turns out incompatible with the available soil, at least in urban context and for buildings of a certain size.

As a second storage technique, we will consider controlled thermal phase-shifting, a device in which the storage material is homogeneously distributed within the ventilating duct, in order to increase the heat-transfer surface and to decrease the penetration distance to the thermal mass. Providing a homogeneous airflow and a good convective exchange, it becomes possible to delay the day/night oscillation almost without dampening, for the night cooling peak to be available in the middle of the day. This technique, which arises from a theoretical work, recently gave rise to the development of a first series of lab prototypes [49].

As an optional downstream complement to preceding techniques (or to direct ventilation), we will finally consider direct evaporative cooling, for further decrease of the air temperature brought to the building by ventilation.

2.2.2. Models

Within this study, modeling of the thermal storage systems (buried pipes, thermal phase-shifting) is performed by way of previously developed and validated analytical models, for a constant airflow. In the case of buried pipes [47], a set of two coupled differential equations account for the convective heat exchange between air and pipe, as well as cylindrical heat diffusion in the soil around the pipe, with adiabatic boundary condition at inter-axial pipe-pipe distance. In the case of the phase-shifting device [49], the physical phenomenon under consideration takes place in a thermal storage similar to a packed-bed, with storage elements sufficiently small for their individual temperature to be regarded as homogeneous (no intra-element temperature gradient), leading to a simplified set of differential equations known as the Schuman model.

In both cases, the core of the model concerns the case of a sinusoidal temperature input:

$$T\Big|_{x=0} = \theta_0 \cos(\omega t) \qquad \text{(Eq.2.1)}$$

Explicit resolution of the associated set of differential equations leads to following temperature output, which is characterized by amplitude-dampening and phase-shifting of the input signal:

$$T = \theta_0 \cdot \exp\left(-\frac{S\,h}{c_a \dot{m}_a}\right) \cdot \cos\left(\omega(t - \frac{x}{v_a}) - \frac{S\,k}{c_a \dot{m}_a}\right) \qquad \text{(Eq. 2.2)}$$

In preceding equations, $\dot{m}$ (kg/s) and v_a (m/s) are the airflow rate and velocity, and c_a (J/kg.K) the specific heat of air.

In the case of the buried pipes S=2πr_0 x is the pipe exchange surface, with r_0 (m) its radius and x (m) its length. The amplitude-dampening and phase-shifting coefficients h (W/K.m^2) and k (W/K.m^2) account for the serial link of (i) convective heat exchange between air and pipe; (ii) heat diffusion in the soil around the pipe. They are given by decomposition in real and imaginary part of:

$$\frac{h_0 h_s}{h_0 + h_s} = h + ik \qquad \text{(Eq. 2.3a)}$$

Where:

$$h_s = \frac{\lambda_s}{\delta} \cdot (1+i) \cdot (-1) \cdot \frac{I_1\left((1+i)\frac{r_0}{\delta}\right) \cdot K_1\left((1+i)\frac{R_0}{\delta}\right) - K_1\left((1+i)\frac{r_0}{\delta}\right) \cdot I_1\left((1+i)\frac{R_0}{\delta}\right)}{I_0\left((1+i)\frac{r_0}{\delta}\right) \cdot K_1\left((1+i)\frac{R_0}{\delta}\right) + K_0\left((1+i)\frac{r_0}{\delta}\right) \cdot I_1\left((1+i)\frac{R_0}{\delta}\right)}$$

(Eq.2b)

$$\delta = \sqrt{\frac{2a_s}{\omega}} \qquad \text{(Eq. 2.3c)}$$

In preceding equations h_0 (W/K.m^2) is the air-pipe convective exchange coefficient, λ_s (W/K.m) and a_s (m^2/s) are the thermal conductivity and diffusivity of the soil, r_0 (m) is the pipe radius and R_0 (m) the total pipe and soil radius (half of the inter-axial distance between the pipes). I_n and K_n are modified Bessel functions of order n.

In the case of the phase-shifting device, *S* represents the total exchange surface of the particles over the system length *x*. In this case, the amplitude-dampening and phase-shifting coefficients *h* (W/K.m^2) and *k* (W/K.m^2) account for the serial link of (i) convective heat exchange between air and pipe; (ii) heat storage in the particles. They are given by:

$$h = \frac{h_0 k_s^2}{h_0^2 + k_s^2} \qquad \text{(Eq. 2.4a)}$$

$$k = \frac{h_0^2 k_s}{h_0^2 + k_s^2} \qquad \text{(Eq. 2.4b)}$$

$$k_s = \frac{\omega c_s \rho_s V_s}{S_s} \qquad \text{(Eq. 2.4c)}$$

In preceding equations h_0 (W/K.m^2) is the air-particle convective exchange coefficient, V_s (m^3), S_s (m^2), c_s (J/K.m^3) and ρ_s (kg/m^3) are the volume, exchange surface, specific heat and density of the storage particles.

For the case of hourly meteorological data over an entire year, Fourier analysis allows to decompose the input temperature into a complete sum of harmonics (from yearly up to hourly frequency), so that the hourly system output temperature can be recomposed by applying preceding models to each one of the harmonics.

Finally, as a complement to these storage techniques (or to direct ventilation from outdoor), evaporative cooling is modelled by:

$$T = T_{in} + \eta (T_{wet} - T_{in}) \qquad \text{(Eq. 2.5)}$$

In preceding equation T_{in} is the input temperature of the evaporative cooling device (given by outdoor, buried pipe or phase-shifting), T_{wet} is the associated wet-bulb temperature, and η the evaporative cooling efficiency.

In the following, the results of these models will be used: (i) for determination of the climatic cooling potential of these techniques, independently of any building (section 2.3); (ii) as an input to building simulation, for determination of the effective savings in cooling demand (section 2.4).

2.2.3. System configuration

In the case of buried pipes, we will here adopt a configuration which consists of 12 cm diameter pipes with 50 cm inter-axial distance, for a specific airflow of 100 m^3/h per pipe (2.5 m/s). According to the model, with such a configuration and a typical soil (1.9 W/K.m conductivity, 1.9 MJ/K.m^3 heat capacity) a 10 m pipe reduces the day/night input amplitude to 41%, whereas a 20 m pipe reduces it to 17% (exponential damping), with a phase-shift which remains lower than an hour (figure 2.2b).

In the case of the thermal phase-shifting device, we will here adopt a configuration which consists of 16 mm diameter PVC tubes that are filled with water, piled up perpendicular to the airflow, with 2 mm spacing between tubes. With a duct cross-section of 50 x 50 cm subject to a specific flow of 100 m^3/h (0.39 m/s average interstitial velocity between tubes), the system enables an 8 h phase-shift within 1.6 m length, respectively a 12 h phase-shift within 2.4 m (linear phase-shifting), for a residual amplitude higher than 80% (figure 2.2c). Note that his system not only differs from the buried pipes in terms of thermal behavior, but also in storage volume, which is almost 10 times inferior.

As can be seen in figure 2.2 b and c, the outlet of the thermal storage systems is at times warmer than the ambient air, in particular at night. It hence becomes interesting to combine the use of the aforementioned storage systems with direct ventilation, taking at each moment the cooler of the two sources (however, such a setup requires a second ventilation fan, since the thermal storage needs to be regenerated at night). We hence will consider following passive cooling systems/configurations, as schematically depicted in figure 2.1:

- Direct: direct ventilation from outdoor
- Pipe10m: 10 m buried pipes, resulting in 41% residual amplitude of day/night oscillation
- Pipe20m: 20 m buried pipes, resulting in 17% residual amplitude of day/night oscillation
- Shift8h: 8h thermal phase-shifting device
- Shift12h: 12h thermal phase-shifting device
- Pipe10m&Direct: combination of 10 m buried pipes with direct ventilation
- Pipe20m&Direct: combination of 20 m buried pipes with direct ventilation
- Shift8h&Direct: combination of 8 h phase-shifting with direct ventilation
- Shift12h&Direct: combination of 12 h phase-shifting with direct ventilation

We finally consider direct evaporative cooling as an optional complement to the preceding techniques (dashed box in figure 2.1), which will be simulated with a constant efficiency of 50% (humidification up to 50% of the potential, as given by the difference between dry and wet bulb temperatures). As a result, we end up with 18 possible passive cooling systems (9 combinations of thermal storage and direct ventilation, with or without evaporative cooling). For a representative set of these systems, figure 2.2 shows the simulated temperature dynamic over a hot summer week, as simulated with meteorological data of Geneva.

2.2.4. Ventilation rate, control and system size

Like for direct night ventilation, in which the airflow may be increased at night to bring fresh air into the building, we can consider the preceding systems with a larger airflow rate than the strict minimum air-change value, as long as the system output temperature is lower than the one of the building. So as to maintain the same system performance (same output temperature), such increased ventilation strategies obviously imply proportional sizing of the evaporative cooling unit as well as of the storage device (buried pipe, phase shifter). Such increased ventilation strategies also imply electric overconsumption, which is to be kept as low as possible. While we will limit our study to the thermal contribution of such systems, we stress that the problem of electricity should eventually be studied carefully.

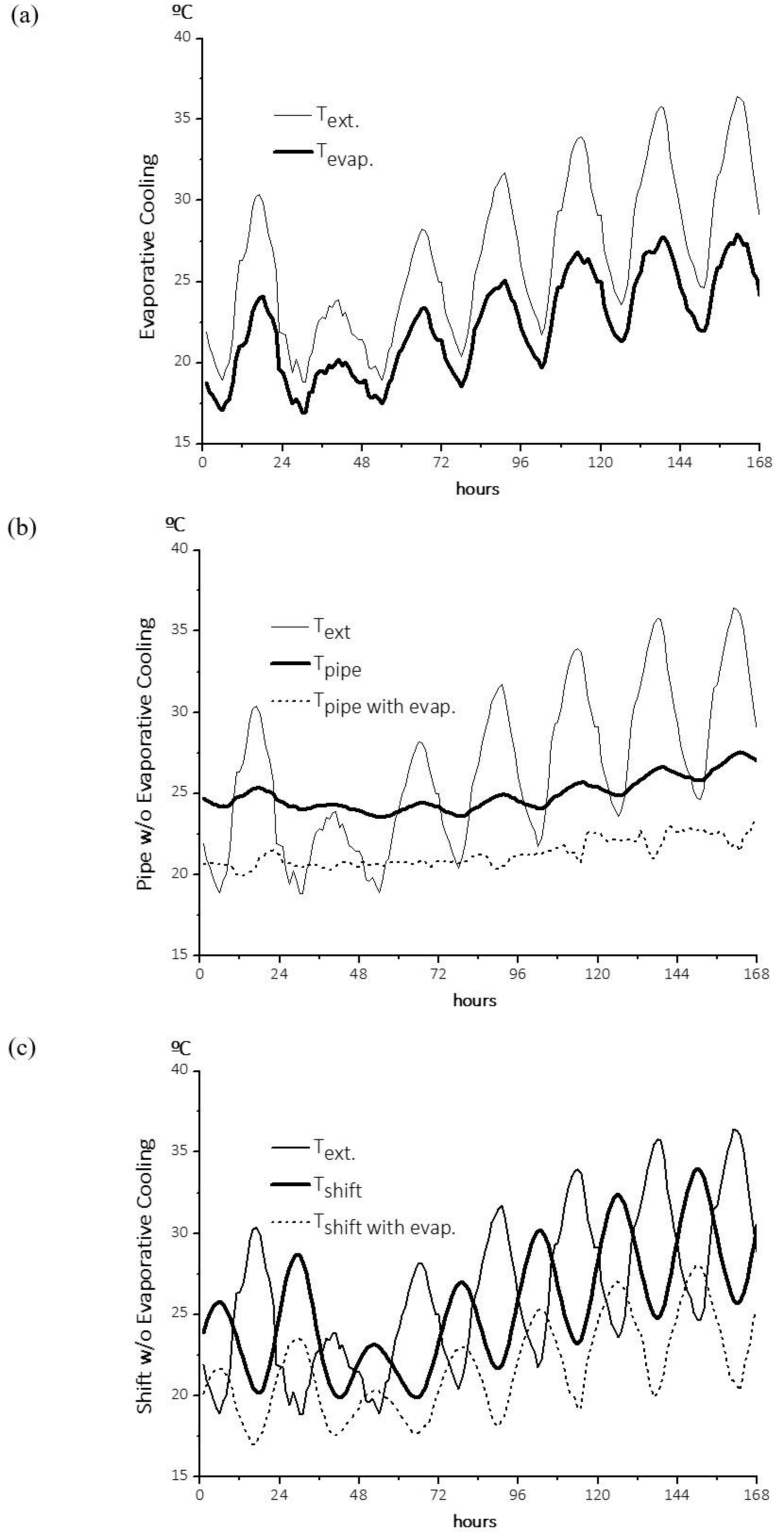

Figure 2.2. Simulated passive cooling systems on a hot summer week. External temperature and output temperatures for the different cooling systems: (a) evaporative cooling system (50% efficiency), (b) buried pipes system (20 m), with and without evaporative cooling, and (c) phase-shifter system (12 h), with and without evaporative cooling.

2.3. Climatic cooling potential and energy savings in buildings

While, for a given climate, the passive cooling systems can be simulated and characterized independently of any building, their effect on the cooling demand of a particular building must in principle be determined by way of integrated dynamic building´s simulation (with ventilation temperature given by the associated passive cooling system). As an alternative, we here develop a simplified method for assessing these energy savings from the knowledge of: i) the characteristic of the passive cooling system, in terms of a climatic cooling potential (CCP) which relates to the temperature of the cooling source and the associated airflow; ii) the characteristic of the building, merely and alone in terms of its cooling demand (Qcool) in absence of passive cooling. Comparison of both values on an appropriate time step leads to the useful cooling potential (UCP) of the passive cooling system for the specific building. The method, which is developed below, is schematically depicted on following flowchart (figure 2.3).

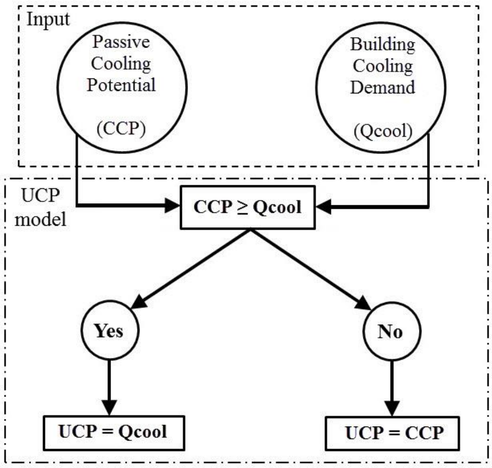

Figure 2.3. Schematic of UCP model

The first step, for a given passive cooling system and associated airflow, is to define its climatic hourly cooling potential (CCP), which expresses the cooling load that the system can bring to a building as compared with ventilation at standard reference flow rate from outdoor:

$$CCP = cm(T_{set} - T_{vnt}) - cm_{ref}(T_{set} - T_{ext})$$

$$m = \begin{cases} m_{vnt} & if \;\; T_{vnt} < T_{bld} \\ m_{ref} & if \;\; T_{vnt} \geq T_{bld} \end{cases} \qquad \text{(Eq. 2.6)}$$

In equation 2.6: *CCP* is the climatic cooling potential for a given hour, in kWh; *c* is the heat capacity of air in kWh/K.kg; *m* and m_{ref} are the rate of ventilation and the reference rate of ventilation in absence of passive cooling, respectively, both in kg/h; T_{set} is the building´s set point temperature in °C; T_{vnt} is the hourly average output temperature of a given passive cooling system in a given hour, in °C; T_{ext} is the hourly average outdoor temperature in a given hour, in °C; m_{vnt} is rate of ventilation for a given passive cooling system, in kg/h; T_{bld} is the building´s hourly average temperature in a given hour, in °C.

Note that the *CCP* is computed by using T_{set} (typically 26°C) instead of the effective building temperature, of which there is no prior knowledge (see discussion further down). It is in this sense that CCP represents a climatic index (dependent on the climate under consideration, the passive cooling system and the flow rate, as well as the comfort set point), independently of any building´s characteristics.

As discussed before, the enhanced flow rate m_{vnt} is reduced to the reference value m_{ref} when its temperature exceeds that of the set point. In this regard, the *CCP* can also be expressed by:

$$CCP = cm_{ref}(T_{ext} - T_{vnt}) + c\left(m_{vnt} - m_{ref}\right)(T_{set} - T_{vnt})_{+} \qquad \text{(Eq. 2.7)}$$

In the latter expression, reduction of the airflow is taken into account by considering only the positive values of the second term. As compared to the reference case, the climatic cooling potential of the passive system hence divides in: i) a first term concerning the reference flow rate, which relates to the input – output temperature differential of the passive cooling system; ii) a second term concerning the additional flow rate, which relates to the set point – system temperature differential, and which is only active when the latter is positive. Note that for the particular case of direct night ventilation, where Tvnt equals Text, the first term reduces to zero, obviously indicating that in this case only increased flow rates can provide a cooling potential as compared to the reference case.

In a second step, for a particular building, the CCP is compared to the cooling load Q_{cool} in absence of passive cooling, which is needed for the building temperature not to rise above T_{set}. Since the CCP is a climatic index, it will at certain times be higher than the actual cooling load of the building (especially during winter season, but possibly also at certain periods of the summer, typically at night). We hence cut off the CCP to its corresponding value of Q_{cool}, over a selected integration time step (hourly, daily, weekly, monthly). Depending on the integration time step, we hence define the annual useful cooling potential (UCP) as follows:

$$UCP_{hourly} = \sum_{h=1}^{8760} MIN(CCP, Q_{cool})$$

$$UCP_{daily} = \sum_{d=1}^{365} MIN(\sum_{h=1}^{24} CCP\,, \sum_{h=1}^{24} Q_{cool})$$

$$UCP_{weekly} = \sum_{w=1}^{52} MIN(\sum_{h=1}^{7\times24} CCP\,, \sum_{h=1}^{7\times24} Q_{cool}) \qquad \text{(Eq. 2.8)}$$

$$UCP_{monthly} = \sum_{m=1}^{12} MIN(\sum_{h=1}^{30\times24} CCP\,, \sum_{h=1}^{30\times24} Q_{cool})$$

In equation 2.8, *UCP* stands for the annual useful cooling potential in kWh, and the subscripts stand for hour, day, week and month, respectively. Q_{cool} is the building´s hourly cooling demand at a given hour, in kWh. Note that in all four cases *UCP* is an annual value, which represents the global savings on cooling demand one might expect from a given passive cooling technique and associated airflow.

In principle, the suitable choice of the integration time step for comparing *CCP* and Q_{cool} relates to the thermal inertia of the building. As a matter of fact, when there is no cooling demand from the building and a certain cooling potential is present, the latter can be stored into the building thermal mass for subsequent use, which is not taken into account by a too small integration time step. On the other hand, a too long time step might lead to overestimation of the passive cooling load that can effectively be absorbed by the building when there is no cooling need. Furthermore, storage of the passive cooling potential will result in lowering the building temperature, which tends to invalidate the use of T_{set} in the calculation of the *CCP*.

In practice, the choice of the integration time step for comparing *CCP* and Q_{cool} will condition the resolution at which latter data should be available. In a particular case this might become a crucial point when trying to access such passive cooling techniques on a large spatiotemporal scale (some hundreds or thousands of km, some decades), where limitation of the data quantity becomes an important issue.

Figure 2.4 shows a schematic representation of the relation between CCP and UCP over a year, for different cooling demands and two different rates of ventilation (left and right). While CCP has its highest value in winter (left and right of time axes), when the Tset – Tvnt differential is at its maximum, it does not correspond to any cooling demand and is therefore of no use. On the contrary, in summer, the cooling demand might exceed the available cooling potential, which cannot be entirely covered by the passive cooling system. This representation allows understanding the relation between cooling demand and airflow rate (and associated system size). While low flow rates allow 100% covering of low cooling demands only (Fig.4, left), their baseline contribution to higher cooling demands might still be of interest. In this respect it is worthwhile noticing that, with increasing cooling demand, the useful cooling potential UCP of the passive system tends to a maximum value, given by the total CCP over the cooling period. Differently, high flow rates (right part of figure 2.4) allow 100% of a wide range of cooling demands, obviously indicating system over sizing in the case of lower demands.

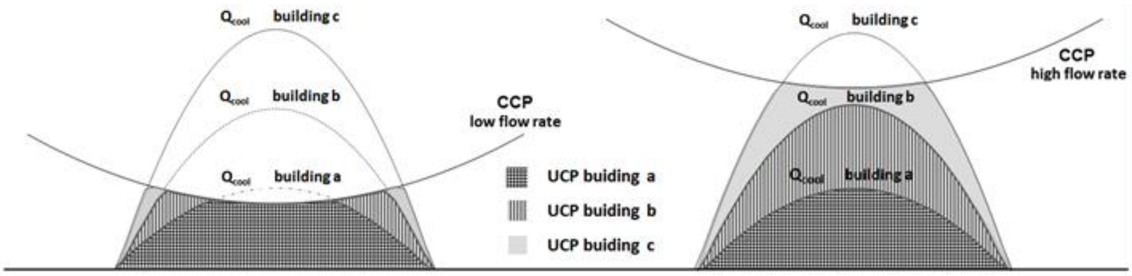

Figure 2.4. Schematic evolution and relation of climatic cooling potential (CCP) and useful cooling potential (UCP) over time, for 2 different rates of ventilation (left and right) and 3 different cooling demands.

Figure 2.5 is a schematic representation of the total number of cases considered in simulation:

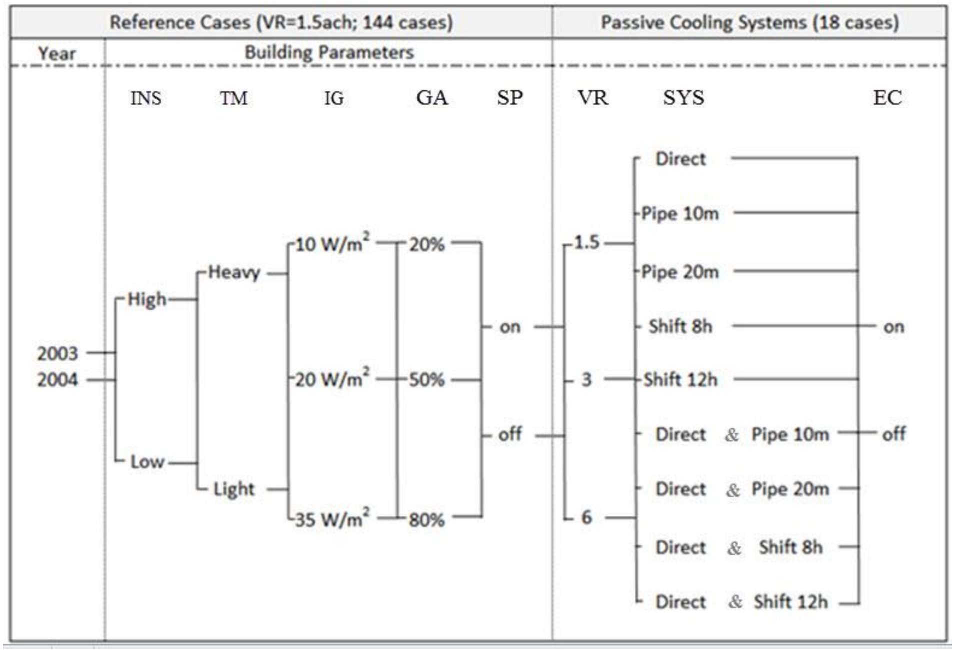

Figure 2.5 Overview of the 7776 simulated combinations: 2 weather data sets, 72 buildings, 18 passive cooling systems, 3 flow rates / system sizes (INS: insulation; TM: thermal Mass; IG: internal Gains; GA: glazing area; SP: solar protection; VR: ventilation rate;.SYS: passive cooling system; EC: evaporative cooling).

2.4.Integrated building simulation

In order to validate the proposed method, to characterize its robustness and its sensitivity to the integration time step, we will compare it to integrated dynamic building simulation (with ventilation temperature given by the associated passive cooling system).

We therefore reach back on a previous study [28] which focused on the potential of the various passive cooling techniques of section 2.2 for the case of an administrative building, located in the moderate climate of Geneva. This study analyses the simulated building cooling demand for a variety of constructive and operational configurations (thermal mass and insulation, window-to wall ratio, solar protection, internal gains), with a specific attention to normal versus a hot summer (as given by 2004 and 2003 urban meteorological data).

The building consists of 20 m^2 / 50 m^3 offices distributed on both sides of a broad central corridor. In terms of simulation, this typology results in a thermal model made up of three zones: two offices, on opposite facades separated by the central corridor, with lateral boundary conditions given by identical interior climate (neighbor offices). The parameters and options that govern the thermal behavior of the building are as follows:

Thermal mass is mainly determined by 28 cm thick slabs, either in heavy option (full concrete: 510 kJ/K.m^2) or in medium option (combined wood structure with concrete filling: 350 kJ/K.m^2). In both cases, separation walls between offices add an additional 170 kJ/K.m^2 (relative to slab surface).

Thermal insulation is either of low 1980's quality (6 cm, double glazing windows), or of high quality as given by the Swiss Minergie standard (20 cm, triple glazing insulating windows).

Solar access is determined by an East-West orientation on a low 5° horizon, along with a 20%, 50% or 80% window-to-wall ratio.

Efficient external solar protection is activated when direct radiation on the façade exceeds 10 W/m2 (overall g-value: 13% with 1980 windows, 7% with Minergie windows). Alternatively, the building can also be simulated without solar protection (overall g value: 68% with 1980 windows, 42% with Minergie windows).

Internal gains are 10, 20 or 35 W/m2 (during occupation: 8-18 h) with a reduction at noon (see figure 2.7 top left: reduction of Qcool at noon due to lower occupation/internal gains).

The total combinations of the preceding parameters correspond to 72 building configurations, which are considered in the context of the 2 meteorological datasets (2003 and 2004), representing a total of 144 reference cases (without passive cooling). For all of these reference cases, the ventilation from outdoor during occupation is 72 m^3/h per office(approximately 1.5ach – 1.5 air changes per hour), dropping at night to 6 m^3/h (0.1 ach).

So as to investigate the impact of the passive cooling systems on the thermal behavior of the referred buildings and so as to validate the model defined in section 2.3, all preceding reference cases were also simulated in combination with the 18 passive cooling systems presented in section 2.2. Finally, associated to these systems, 3 possible controlled flow rates (and associated system sizes) are considered:

Same nominal rate as for reference cases (72 $m^3/h \cong 1.5$ ach), however also activated at night if the ventilation temperature is cooler than the building.

Twice the reference rate (144 $m^3/h \cong 3$ ach), activated as long as the ventilation temperature is cooler than the building (else reduced to the reference flow).

Four times the reference rate (288 $m^3/h \cong 6$ ach), activated according to the same rule.

In this way, we study 54 passive cooling configurations (18 systems in combination with 3 flow rates). The flow rates were selected to allow a vast analysis, varying from a low flow rate (1.5 ach) to a high flow rate (6 ach).

Altogether, the 54 passive cooling configurations associated to the 72 building and 2 weather data sets represent a total of 7776 (54x72x2=7776) integrated system cases, as schematically represented in Figure 2.5.

Simulation over the summer period (May-September) is carried out in two steps, with an automated overall approach:

For both the meteorological data sets, the passive cooling systems are simulated by way of the specific analytical models developed previously described in section 2.2, yielding hourly data over an entire year. System control and building response are then simulated within TRNSYS [50].

2.5. Results and discussion

2.5.1. Effective savings

Before exploring the simplified UCP method developed in section 2.3, we start by giving a synthetic overview of the effective savings in cooling demand, as obtained by numerical simulations. Focus is set on direct ventilation, 12h phase shifting and combination of both, each being associated or not with evaporative cooling. Each of the 6 systems is associated with the 3 possible airflow rates (with corresponding system size) and the two meteorological data sets.

In figure 2.6, each symbol represents the overall annual simulation result for one of the 144 reference cases referred above. The value on the x-axis corresponds to the cooling demand of the particular configuration in absence of passive cooling (Q_{cool}, reference cases), while the value on the y-axis (ΔQ_{cool}) corresponds to the savings in cooling demand when using the passive cooling system. The general structure of these plots illustrates the discussion held in section 2.3: while a low flow rate (small system) allows 100% covering of low cooling demands, it only covers a fraction of higher demands, where its contribution is eventually limited to a maximum value given by the available cooling potential over the entire cooling season. On the left side of the plots (especially in the case of evaporative cooling), the similar contribution of the different flow rates shows that limited cooling can be completely covered with small systems.

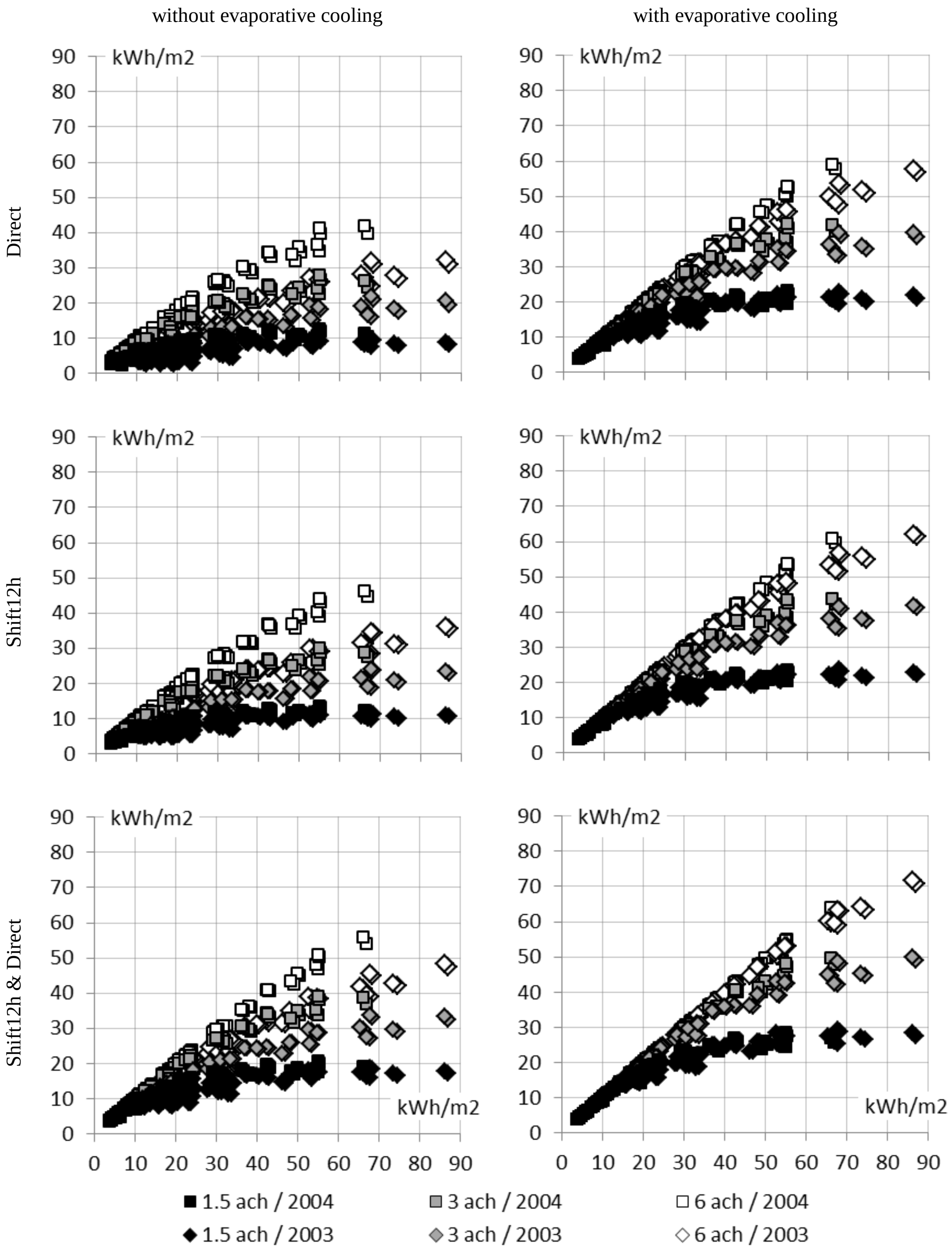

Figure 2.6. Savings in cooling demand (ΔQcool: vertical axis) in function of cooling demand in absence of passive cooling (Qcool: horizontal axis) for the 72 reference buildings and the 2 meteorological data sets (144 reference cases).

A comparison between the different systems brings about the following general insights:

- As compared to direct ventilation, standalone thermal phase shifting carries only small additional annual savings in cooling demand (15% in average over all buildings and years). The basic reason therefore relates to the fact that the systems works on storage of the day-night temperature oscillation, a function which can basically also be achieved by the building if it has enough thermal inertia.

- In this regard, combination of phase-shifting with direct night ventilation, which takes advantage of the night cooling peak “twice a day”, allows an average of 58% additional savings (with relatively important variations from case to case, depending in particular on the airflow rate and the meteorological year under consideration).

- Finally, at least in the particular case of Geneva, direct evaporative cooling brings about an important potential, even for buildings with important cooling demand. Furthermore, the discrepancy between the standard summer of 2004 and the hot summer of 2003 is reduced, due to relatively similar water content of the air (similar wet bulb temperature).

Additionally, the effect of thermal mass can also be viewed in figure 2.6: each “line” of withe, gray and black squares is composed by sets of two squares, normally close from each other. The dots with higher values in the vertical axis (higher savings) belong to the building with higher thermal mass, these squares also tend to present a lower cooling demand (squares are upwards and left shifted).

A more detailed discussion on these points can be found in the specific publication concerning the numerical study [28].

2.5.2. Dynamic over a typical week

The relation between the simulated savings and the simplified UCP method will now be illustrated for a specific building (50% window-to-wall ratio, external solar protection, 35 W/m^2 internal gains, Minergie standard thermal insulation), and a hot summer (2003). The 3 passive cooling systems are those of section 2.2, without evaporative cooling.

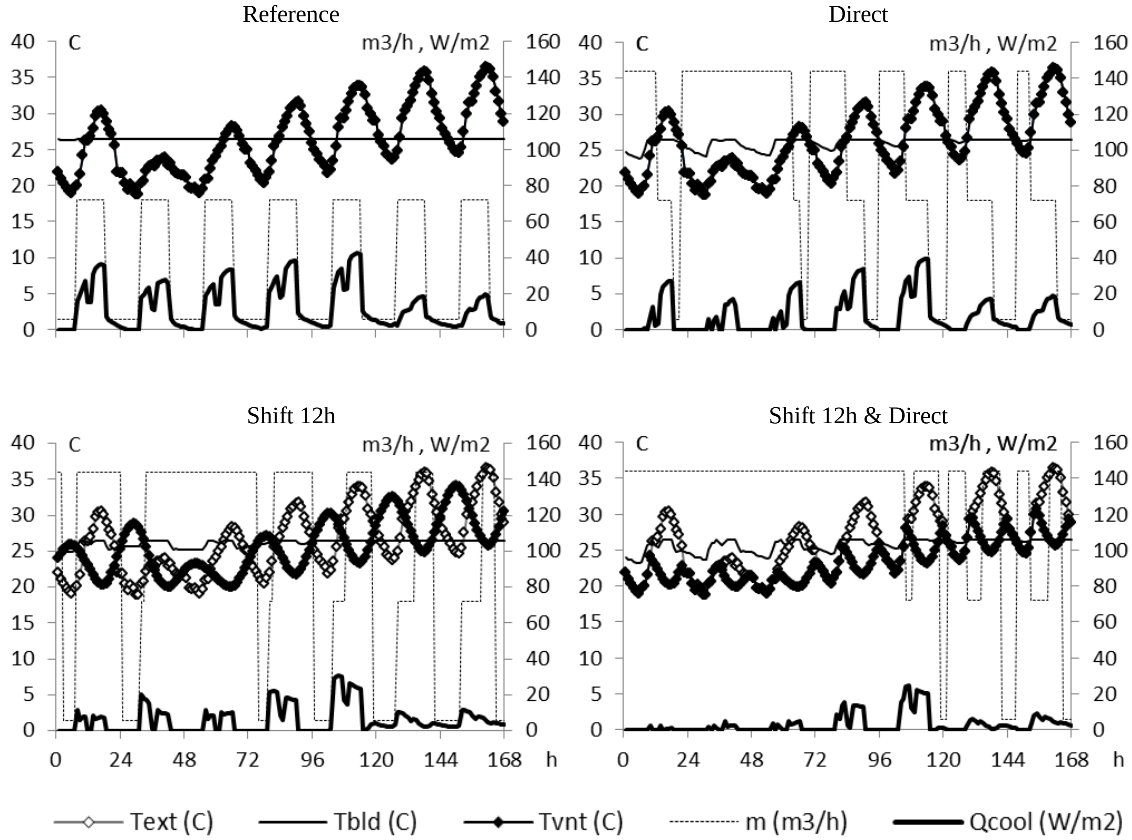

Figure 2.7. Outdoor, building and ventilation temperatures (Text, Tbld, Tvnt), as well as ventilation flow rate and resulting cooling demand (m and Qcool) over a typical summer week.

Figure 2.7 shows the hourly evolution of the outdoor, indoor, and ventilation temperatures, as well as the ventilation flow rate and resulting cooling demand over a typical summer week.

In the reference case, ventilation at standard 1.5 ach (72 m^3/h) flow rate is activated during occupation (8 - 18h). During this period, internal gains (and to minor extent outdoor temperature and solar radiation) result in a significant cooling demand (up to 42 W/m^2 on day 5), which drops when internal gains are reduced (at noon) or null (during the week end, day 6 and 7). As a first alternative, direct cooling from outdoor with 3 ach (144 m^3/h) allows to store the freshness of the night in the building, resulting in a lower cooling demand during the following day. Note that when the outdoor temperature rises above that of the building (in particular during occupation/daytime), the flow rate is reduced to its reference value; on the contrary, when the outdoor temperature remains below that of the building (day 2), enhanced ventilation can extend over 24h. As a second alternative, by inverting the day/night oscillation, the 12h phase-shifting device allows for enhanced ventilation and corresponding passive cooling during daytime, resulting in a further reduction of the cooling demand, and particularly of the peak load. Finally, combination of phase-shifting and direct ventilation allows for almost constant over-ventilation with “fresh” air, and hence for a further reduced cooling demand.

Figure 2.8 allows comparison of the climatic potential (CCP), which is calculated from mere knowledge of the reference flow rate and set point temperatures (equation 2.6 or 2.7), with the effective savings in cooling demand which result from simulation.

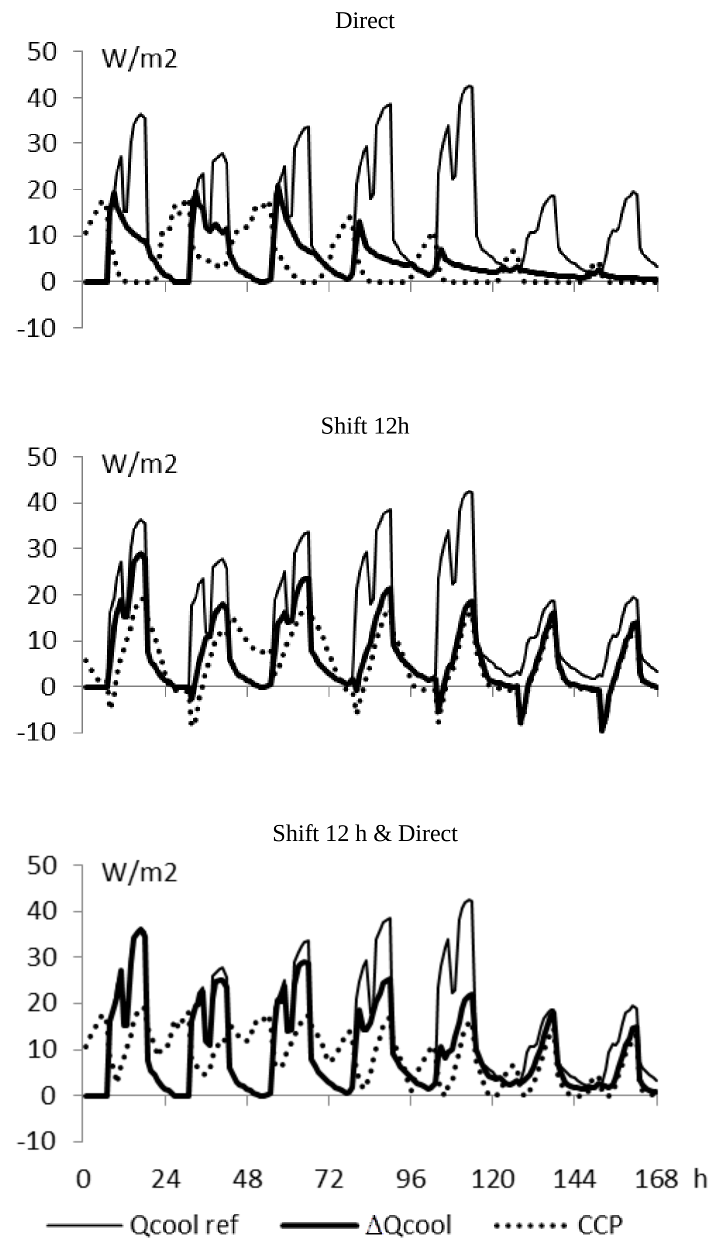

Figure 2.8. Climatic cooling potential (CCP) and effective savings in cooling demand (ΔQcool), as well as cooling demand of reference case (Qcool ref) over a typical summer week.

Table 2.1. Integrated savings in cooling demand for 3 passive cooling systems: i) reference cooling demand and effective savings (Qcool and ΔQcool); ii) climatic and useful cooling potential (CCP and UCP), as well as relative error in relation to the effective savings.

	Direct	Shift12h	Shift12h & Direct
	kWh/m^2	kWh/m^2	kWh/m^2
Qcool	31.7	31.7	31.7
ΔQcool	13.0	15.5	20.9
CCP	33.2	33.7	49.3
UCP.hour	4.8	11.1	14.5
UCP.day	13.9	14.6	20.4
UCP.week	15.5	16.5	23.5
UCP.month	15.3	16.2	24.4
ΔUCP.hour	-63%	-28%	-31%
ΔUCP.day	8%	-6%	-3%
ΔUCP.week	19%	7%	12%
ΔUCP.month	18%	5%	17%

In the case of direct ventilation from ambient, the effective savings occurring during daytime are of the same order of magnitude as the CCP, which is available during night time, illustrating the effect of the building´s thermal inertia. On the contrary, in the case of 12h phase-shifting the CCP synchronizes fairly well with the demand and hence with the savings. In this particular case we also note a short negative value in energy saving and CCP in the morning when the temperature of the phase-shifting device: i) is lower than the building, enabling for enhanced ventilation for cooling; ii) is still higher than outdoor, resulting for the reference flow rate in a lower cooling potential than with direct ventilation (see equation 2.7). As a last alternative, combination of phase-shifting and direct ventilation results in a CCP available twice a day, which induces increased savings as compared to preceding alternatives.

Table 2.1 presents the results of the 3 systems as integrated over the entire summer (May – September): i) the reference cooling demand and the effective savings, as given by simulation; ii) the climatic cooling potential and the useful cooling potential, as calculated via equation 2.8, as well as the relative error in relation to the effective saving.

In the case of direct ventilation, numerical simulation yields 13.0 kWh/m^2 savings as related to 31.7 kWh/m^2 demand for the reference case. UCP correlates quite unfairly with these savings when calculated on an hourly basis (63% underestimation). This is due to the fact that the CCP and cooling demand take place at different moments and do only correlate via the building inertia, which is not taken into account by the UCP calculation. The best correlation with the effective savings is obtained when the UCP is calculated on a daily basis (8% over estimation), but reasonable values are also obtained on weekly or monthly basis. In the case of 12h phase-shifting, the effective savings amount to 15.5 kWh/m^2. This value is again underestimated with a UCP calculated on hourly basis, indicating a remaining mismatch between hourly CCP and demand. Very good values are however obtained with higher integration time steps (around 5% error in each case). Finally, similar results are obtained for the combination of phase-shifting with direct ventilation. It is worthwhile mentioning that, in all cases, the UCP method gives a much better estimation of the effective savings than the previously developed CCP method, which does not take into account the building demand.

2.5.3. Simplified method versus numerical simulation

The previous analysis is finally carried out for all the combinations of the 72 buildings, 2 weather data sets, 3 airflow rates and 18 passive cooling systems, presented in section 2.2. For each configuration, the relation between the effective savings and the corresponding UCP over the entire period (May – September) is presented in Figure 2.9 (one symbol per configuration in each plot).

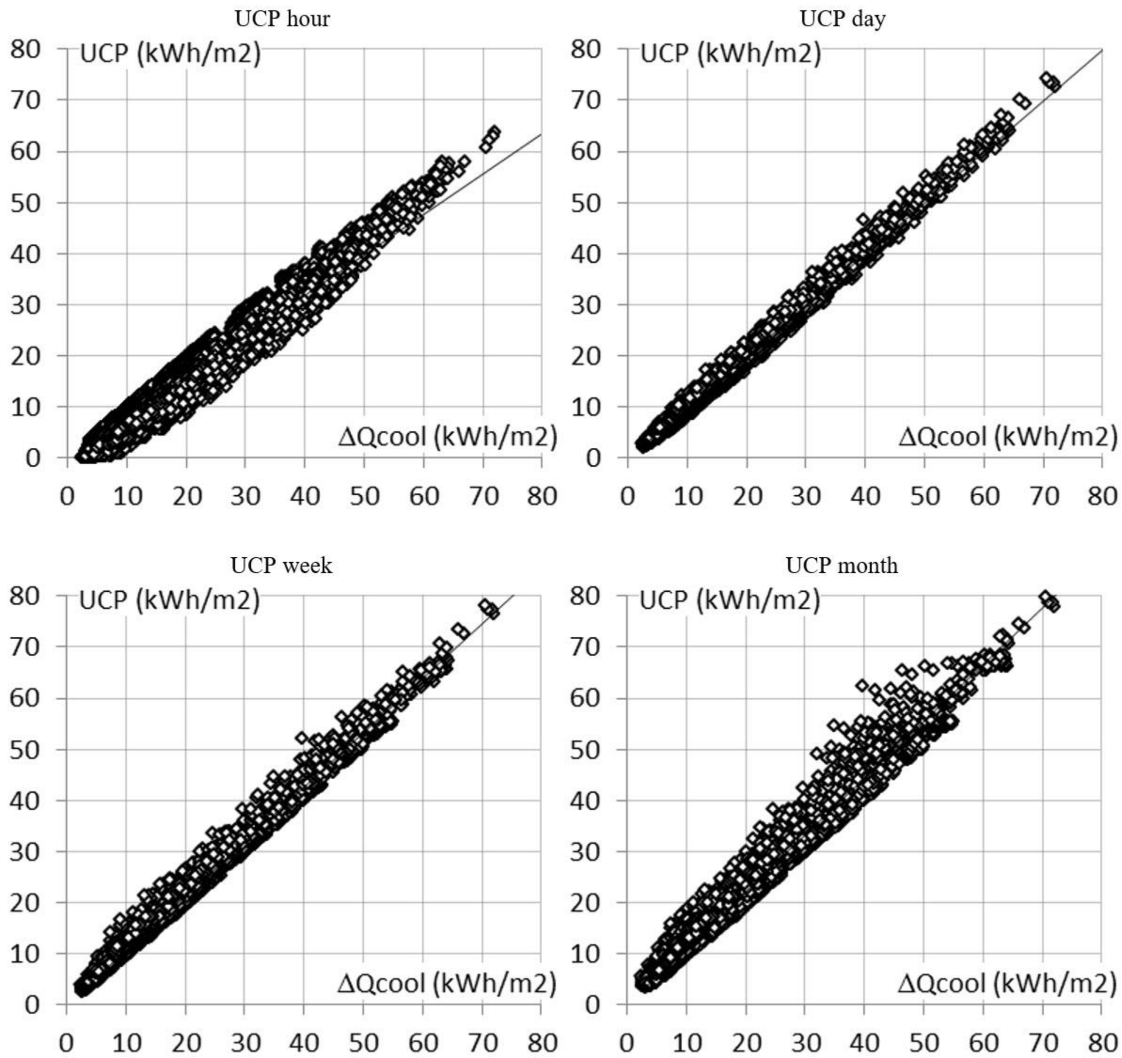

Figure 2.9. Useful cooling potential (UCP) versus effective savings ΔQcool, for the different passive cooling systems and buildings.

As pointed out in section 2.3, and as discussed for a particular case in section 2.2, calculation of the UCP on an hourly basis underestimates the effective savings by an average of 31% (as given by linear regression), due to the fact that the building´s thermal inertia is not taken into account. In comparison, calculation of the UCP on a daily basis reproduces the effective savings with less than 1% error in average. Calculation on a weekly or monthly basis tends on its turn to overestimate the effective savings (average of 6% and 11%), due to overestimation of the available thermal inertia.

These average correlations vary according to the passive cooling system (table 2.2). As pointed out before, the worst correlation goes for direct ventilation from ambient (without evaporative cooling), for which the daily UCP calculation leads to an average 47% underestimation, and the monthly UCP to an average 31% overestimation. All other systems remain, in average, within the 7% error in daily calculation, respectively within the 23% error in monthly calculation.

Table 2.2. Average correlation (linear regression) between useful cooling potential UCP and effective savings ΔQcool, for the different passive cooling systems, with and without evaporative cooling (Dry/Hum).

	UCP.hour		UCP.day		UCP.week		UCP.month	
	Dry	Hum	Dry	Hum	Dry	Hum	Dry	Hum
Direct	0.53	0.74	1.07	1.01	1.21	1.08	1.31	1.11
Pipe10m	0.70	0.81	1.03	1.00	1.13	1.05	1.23	1.08
Pipe10m & Direct	0.66	0.80	1.04	1.01	1.14	1.05	1.22	1.08
Pipe20m	0.76	0.83	1.02	1.00	1.09	1.04	1.19	1.07
Pipe20m & Direct	0.71	0.82	1.03	1.01	1.12	1.05	1.18	1.07
Shift8h	0.82	0.87	0.93	0.97	1.06	1.03	1.14	1.06
Shift8h & Direct	0.78	0.85	0.98	0.99	1.08	1.03	1.13	1.06
Shift12h	0.76	0.84	0.96	0.99	1.09	1.05	1.18	1.08
Shift12h & Direct	0.76	0.83	0.99	1.00	1.09	1.04	1.15	1.06
All systems	0.79		1.00		1.06		1.11	

The dispersion in relation to these average values will now be analyzed for the particular case of daily and monthly calculation of the UCP. In a first step, the analysis concerns the error of the UCP method relatively to effective savings ΔQcool given by simulation. In daily basis, the absolute difference between UCP and effective savings ΔQcool never exceeds 6.8 kWh/m^2, and in half of the cases (2nd and 3rd quartiles of each class) this difference remains below 2.7 kWh/m^2. The dispersion is relatively uniform across the different classes. As a consequence, the relative error (figure 2.10) is much more important for low than for high values of ΔQ_{cool}: up to 38% error for effective savings in the range of 0-10 kWh/m^2 (although the error remains below 8% for the 2nd and 3rd quartiles), but always less than 10% for effective savings above 50 kWh/m^2 (below 4% for the 2nd and 3rd quartiles). In the case of calculation in a monthly basis, the dispersion is much more important, as well in terms of absolute error as in terms of relative error (with a maximum error of 140% in the range of 0-10 kWh/m^2).

However, depending on the importance of the reference cooling demand, a low value of effective savings may or not represent an important passive cooling fraction $\Delta Q_{cool}/Q_{cool}$ (see figure 2.6). As a consequence, preceding dispersion analysis is extended to the error of the UCP method relatively to the passive cooling fraction (figure 2.11). When calculated on a daily basis, the UCP method reproduces the passive cooling fraction very well. In extreme cases, an underestimation up to 20% may occur for high passive cooling fractions (in particular when related to low cooling demands, hence to low absolute savings), but in half of the cases (2nd and 3rd quartiles) the error remains below 6%. When computed on monthly basis, the UCP method tends to overestimate the passive cooling fraction. Hence, in extreme cases, the method indicates close to 100% coverage of the demand whereas the effective fraction only amounts to 30% (70% error). However, for half of the cases of each class (2nd and 3rd quartiles) the error remains below 20%.

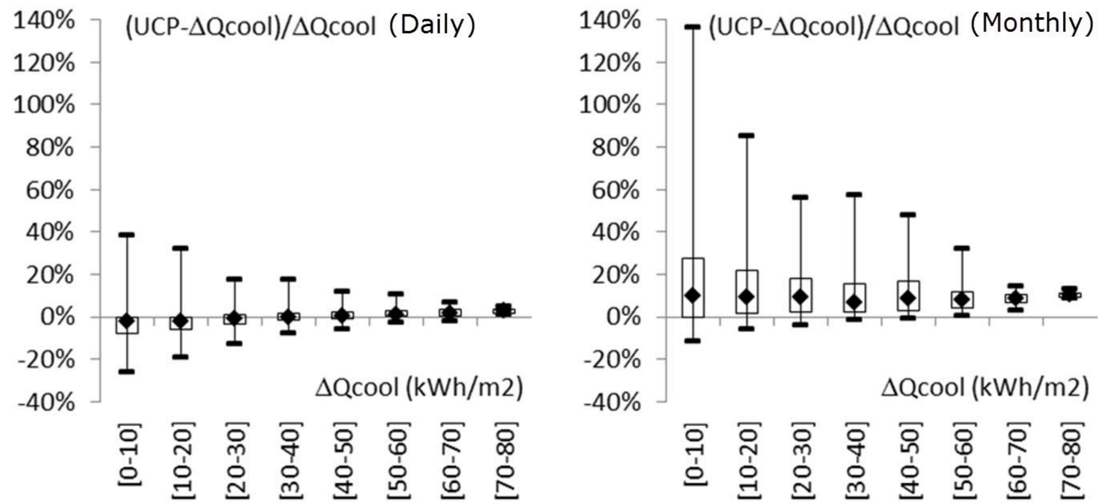

Figure 2.10. Relative error of the useful cooling potential (UCP) method (min, max, median, 2nd and 3rd quartiles), in daily and monthly basis, relatively to effective savings ΔQcool.

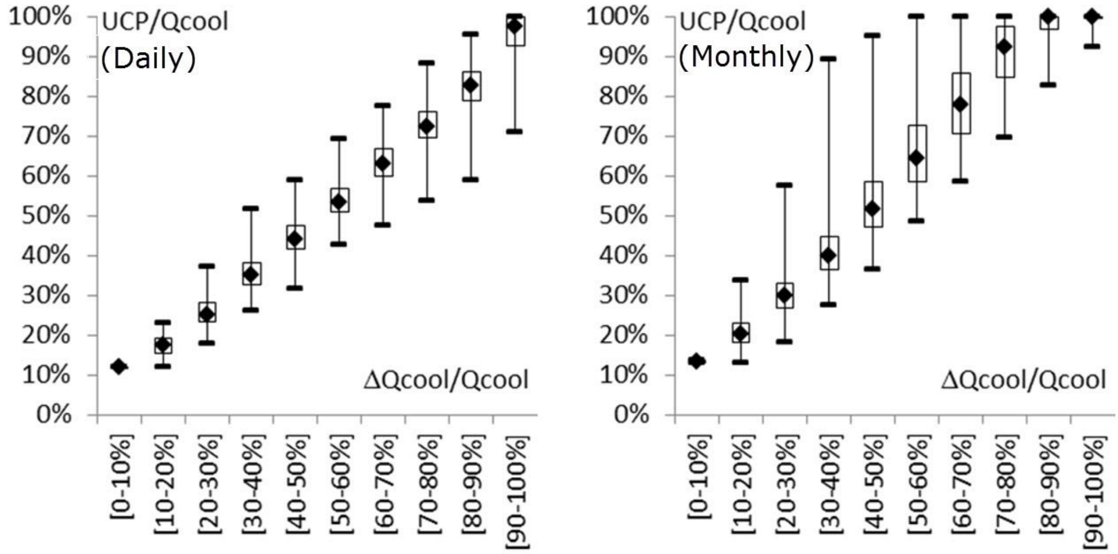

Figure 2.11. Relative error of the useful cooling potential (UCP) method (min, max, median, 2nd and 3rd quartiles), in daily and monthly basis, relatively to the passive cooling fraction ΔQcool/Qcool

2.6. Conclusions

We developed and tested a simplified method for computing the building´s cooling demand savings by use of passive cooling systems based on ventilation (direct ventilation, air-soil heat exchangers, controlled thermal phase-shifting, evaporative cooling, as well as possible combinations thereof).

The systems are characterized in terms of a climatic cooling potential, independently of any building. In a second step, the climatic cooling potential is compared to the cooling load of a particular building, yielding the associated useful cooling potential. Key point of the method is to choose an appropriate time resolution, for taking into account of the building thermal inertia.

The method is tested against an extensive numerical simulation campaign, combining diverse passive cooling systems and sizes with diverse constructive and operational modes for an administrative building situated in Geneva (7776 configurations).

In a first step, correlation between the two methods is analyzed in terms of annual energy savings. Calculation of the useful cooling potential on an hourly basis underestimates the effective savings by an average of 31%, due to the fact that the building thermal inertia is not taken into account, while calculation of the useful cooling potential on a daily basis reproduces the effective savings with less than 1% error in average. Calculation on a weekly or monthly basis tends on its turn to overestimate the effective savings (average of 6% and 11%), due to overestimation of the available thermal inertia. The dispersion in relation to these average values is analyzed for the particular case of daily and monthly calculation basis. Focus is set on the passive cooling fraction (fraction of the demand which can be covered by the passive cooling system). It is shown that, if the data is available in monthly values, the model will tend to overestimate the passive cooling fraction. The error remains below 20% for half of the cases, although it may be quite more important (up to 70%) for extreme cases, in particular in cases where the model indicates close to 100% coverage and the associated cooling demand is low.

As a main result, the method can hence be used for setting up of a climatic potential database in monthly time step, for rough assessing of the potential of these passive cooling techniques on a large spatiotemporal scale (some hundreds or thousands of km, some decades). Much more precise results could be obtained with data in daily resolution (less than 6% error in half of the cases), which however would require setting up of a very extensive database of the climatic potential, as well as knowledge of the corresponding building cooling demand. In this respect, finer evaluation of a particular case should rather use integrated simulation of the passive cooling system and building in hourly time step. Finally, for additional insight, both methods (UCP and detailed numerical simulation) should further be compared to results from real scale installations.

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

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 spatiotemporal scale. Secondly, this assessment relies on high resolution climate dataset built using a regional climate model covering the Iberian Peninsula (IP) with a 9km 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 1kWh per m^3 of building and 3kWh 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.

Keywords: passive cooling; climatic cooling potential; cooling demand savings; renewable energy resources; Iberian Peninsula

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 (ºC)
T_{vnt}	passive cooling system output temperature (ºC)
T_{set}	building´s set point temperature (ºC)
T_{ext}	outdoor temperature (ºC)
UCP	useful cooling potential (kWh/m3 of ventilated building)
Q_{cool}	building´s cooling load (kWh)
ΔQ_{cool}	effective savings (kWh)
η	evaporative cooling system´s efficiency
T_{wb}	wet bulb temperature (ºC)
ach	air changes per hour (h^{-1})

3.1.Introduction

3.1.1. 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%) [51]. 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 [23-26]. 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 [8, 12, 52], 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 forced), using the naturally available thermal gradients through openings (natural) or both ways [13]. 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 [27-31], though the efficiency is mainly related to the difference between indoor and outdoor temperatures, the air flow rate, the building´s thermal mass [27] 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 [32]. Evaporative cooling techniques have been proved feasible both from economic and technical stand points through numerous studies [33- 36], 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 [37].

3.1.2. 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. [13] 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 [14-16].

Recently, Campaniço et al. [53] 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 Cooling Potential model (UCP) 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.

3.1.3. 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 [54] and ERA-Interim [55], from the National Centres for Environmental Prediction [56], and the Twentieth Century Reanalysis Project [57], and others. Simultaneously, a large number of Global Climate Models (GCMs) have been used to build climate change scenarios. This effort has been fruitful in generating global climatic information for the 20th century in easy to use regular or quasi-regular grids.

Reanalysis and climate scenario datasets have coarse horizontal resolutions, typically between 1º and 4º (in both latitude and longitude), good enough to reproduce many aspects of large-scale climate [58], but unable to represent many processes and systems that drive regional and local climate variability, where the consequences of climate change will be mostly felt. These limitations are greatly amplified in areas of difficult geomorphology, like complex orography, irregular coastlines, and regions with heterogeneous land cover, where regional and local thermal and mechanical circulations are forced by surface heterogeneity.

To overcome these problems, different downscaling approaches have been advanced. Statistical methodologies [59] use observed relationships between variables at different scales to estimate finer scale properties, but have a major drawback: the observed relationships may not persist in a changing climate. Regional climate models (RCMs) constitute an increasingly popular alternative [60- 64]. RCMs, forced by GCMs or by reanalysis data, are able to capture physically consistent regional and local circulations [65- 69] at the required horizontal and temporal scales, allowing for the development of high-resolution climatologies in any terrain conditions, and when forced by reanalysis fill the gaps of observational networks. Results from different RCMs forced by ERA-40 reanalysis, like those of PRUDENCE [63,70] and ENSEMBLES [71] European projects are a valuable source of atmospheric data for Europe, and in particular for Iberia. Furthermore, results from high resolution RCMs forced by ERA-interim constitute the best climate datasets for Europe and in particular for the Iberia, and have been used very successfully for different economic sectors, like agriculture, forestry and especially renewable energy sources. These climate datasets are used to characterize the present resource in a very detailed manner and to assess the climate change impact on the referred sectors. The added value of these results is both due to the detailed spatial resolution and the time sampling used, allowing the production of hourly data crucial for wind energy, solar energy and potential climatic cooling assessment.

3.1.4. Objectives and outline

The methodology presented in this study has been designed to explore the value of quality climate data, either observational or from regional climate modelling, enabling for the direct assessment of building´s cooling demand savings by the use of ventilated passive cooling systems. From this new innovative methodology it is possible to obtain a preliminary estimation of the cooling demand savings provided by each of the passive systems considered, for different air flow rates (associated to the passive systems) for any climate or region without the need to use building thermal simulation and in a way independent of any building properties. We apply this methodology for direct ventilation and evaporative cooling to a high quality present climate dataset covering the Iberian Peninsula (IP), generated using a state-of-the-art regional climate model, having a high spatial resolution. In the following section we will present the referred methodology and in section 3.3 the description of the meteorological input that is used to create the database that allows for the estimation of cooling demand savings in the IP, which is shown in section 3.4 along with a comparison between the two systems and a sensitivity analysis to the passive cooling system´s air flow rate. Finally, at section 3.5, we present the main conclusions of the present study.

3.2. Methodology

The method used in the present study closely follows Campaniço et al. [53], however, here we characterize any given passive cooling system based on ventilation in terms of its climatic cooling potential CCP in such a way that allows for the assessment of the cooling demand savings provided by it use for any building for any spatiotemporal scale, which was not established in Campaniço et al [53]. In the referred study, CCP was determined in order to allow to compute the cooling demand savings by the use of different passive cooling systems based on ventilation for a specific case/building, here, this climatic index is redefined in such a way that it permits to access the cooling demand savings by the use of different passive cooling systems based on ventilation but for a large spatiotemporal scale and for any building. The CCP relates the temperature of the cooling source Tvnt and the associated air flow rate v, to the cooling load which a passive cooling system brings to a building at temperature Tbld, in reference to ventilation at standard reference air flow rate vref from outside:

$$CCP = c \cdot \rho \cdot v \cdot (T_{bld} - T_{vnt}) - c \cdot \rho \cdot v_{ref}(T_{bld} - T_{ext})$$

$$v = \begin{cases} v_{vnt} & if \;\; T_{vnt} < T_{bld} \\ v_{ref} & if \;\; T_{vnt} \geq T_{bld} \end{cases} \qquad \text{(Eq. 3.1)}$$

Note that: (i) the system may be designed at a higher flow rate v_{vnt} than the standard flow rate v_{ref}, enhancing the cooling load, but should be reduced to v_{ref} when the source temperature is higher than the building; (ii) the flow rates which are used here are building specific (in terms of air change per hour), so that the *CCP* is expressed in kW per m^3 building (or kWh per m^3 building when integrated over a certain period).

In absence of prior knowledge of the building response, the above defined CCP is actually evaluated at a comfort set point T_{set} (instead of T_{bld}). It is in this sense that the CCP represents a climatic index (dependent on the climate under consideration, the passive cooling system and the flow rate, as well as the comfort set point), independently of any building characteristics.

Since the CCP is a climatic index, it will at certain times be higher than the actual cooling load of the building (in particular during the winter season, but possibly also at certain periods of the summer, typically at night). For assessment of the effective contribution, in terms of thermal energy savings for a particular building, the CCP must hence be compared to the cooling load Q_{cool} in absence of passive cooling which is needed for the building temperature not to rise above T_{set}. This comparison, which is done over a certain integration time step, allows the reduction of the CCP to the useful cooling potential *UCP* for the particular building. Depending on the integration time step, we hence define the annual useful cooling potential as follows:

$$UCP_{hourly} = \sum_{h=1}^{8760} MIN(CCP, Q_{cool})$$
$$UCP_{daily} = \sum_{d=1}^{365} MIN(\sum_{h=1}^{24} CCP\,, \sum_{h=1}^{24} Q_{cool})$$
$$UCP_{weekly} = \sum_{w=1}^{52} MIN(\sum_{h=1}^{7\times24} CCP\,, \sum_{h=1}^{7\times24} Q_{cool}) \qquad \text{(Eq. 3.2)}$$
$$UCP_{monthly} = \sum_{m=1}^{12} MIN(\sum_{h=1}^{30\times24} CCP\,, \sum_{h=1}^{30\times24} Q_{cool})$$

In this respect, one of the crucial points is to determine the temporal precision at which the cooling system (CCP) and separately the building (Q_{cool}) have to be characterized. In principle, the suitable choice of the integration time step for comparing *CCP* and *Qcool* relates to the thermal inertia of the building. As a matter of fact, when there is no cooling demand from the building and a certain cooling potential is present (in particular for direct night cooling), the latter can be stored into the building thermal mass for subsequent use, which is not taken into account by a too small integration time step (in particular hourly). On the other hand, a too long time step will lead to overestimation of the passive cooling load that can effectively be absorbed by the building.

For this sake, the simplified method presented by Campaniço et al [53] was tested against an extensive numerical simulation campaign [53], concerning: (i) the case of an administrative building located in Geneva, with a variety of constructive and operational configurations (solar protection, thermal mass and insulation, internal gains); (ii) an important set of passive cooling techniques (direct ventilation, evaporative cooling, air-soil heat exchangers, thermal phase-shifting, as well as combination thereof) with diverse sizing and flow rates.

For the 7776 configurations, correlation between the two methods was analysed in terms of annual cooling energy savings. It was shown that calculation of the UCP on an hourly basis underestimates the effective savings by an average of 31%, due to the fact that the building thermal inertia is not taken into account, while calculation of the useful cooling potential on a daily basis reproduces the effective savings with less than 1% error in average. Calculation on a weekly or monthly basis tends in turn to overestimate the effective savings (average of 6% and 11%), due to overestimation of the available thermal inertia. The dispersion in relation to these averaged values was analysed for the particular case of daily and monthly calculation basis. Focus was set on the passive cooling fraction (fraction of the cooling demand which can be covered by the passive cooling system). It is shown that, if the data is available in monthly values, the model will tend to overestimate the passive cooling fraction. The error however remains below 20% for half of the cases, although it may be quite more important (up to 70% for extreme cases, in particular in cases where the model indicates close to 100% coverage and the associated cooling demand is low). As a main result, the new method of equation 3.1, can therefore be used for setting up of a climatic potential database in a monthly time step, for roughly assessing the potential of these passive cooling techniques on a large spatiotemporal scale (some hundreds or thousands of km, some decades), for which integrated building simulation becomes prohibitive. Much more precise results could be obtained with data on daily resolution (less than 6% error in half of the cases), which however would require the setting up of a very extensive database of the climatic potential and the knowledge of hourly cooling demand. In this respect, finer evaluation of a particular case should rather use integrated simulation of the passive cooling system and building in hourly time step.

On the basis of preceding results we will now establish a CCP database for the Iberian Peninsula (IP), on monthly basis, concerning direct ventilation and evaporative cooling.

As climatic input, a 19 years high resolution hourly climate dataset for the IP mainland is used (see section 3.3). In the case of direct ventilation, T_{vnt} is given by the dry bulb ambient air temperature, T_{ext}, while evaporative cooling is simulated with a constant efficiency η of 50% (in relation to the wet bulb temperature T_{wb}):

$$T_{vnt} = T_{ext} + \eta(T_{wb} - T_{ext}) \qquad \text{(Eq. 3.3)}$$

On the basis of equation (3.1) the CCP will be computed for the case of a comfort set point T_{set} of 26°C, with a reference flow rate vref of 1.5 ach (of 1.5 m^3/h per m^3 building) during daytime (7h – 19h), dropping to zero during the night (representative of an administrative building). The passive cooling system will be assessed for 3 different design flow rates v_{vnt} : (i) 1.5 ach (same as the reference case, but also activated at night if T_{vnt} is below T_{set}); (ii) 3.0 ach (reduced to reference if T_{vnt} is higher than T_{set}); (iii) 6.0 ach (with same controlled reduction).

Given CCP one can easily assess the monthly energy savings provided by the passive systems simply by computing the product between $UCP_{montlhy}$ (equation 3.2) and the building's volume (m^3 of ventilated building).

3.3. Climate data

The current paper uses surface meteorological data from a high resolution climate simulation, performed with the state-of-the-art atmospheric model. The Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) [17] used is a non-hydrostatic model, suitable for simulating a wide range of scales, from large eddy simulation to mesoscale model, with a large number of available options for the model core and the physical parameterizations, making it very competitive for numerical weather prediction, mesoscale meteorological studies and building the high quality climate dataset. The WRF version used here corresponds to its 3.1.1 cycle. Recently, WRF has been extensively used for dynamical downscaling for regional climate studies [72- 79] revealing very good performance in generating hind casts to applications on the energy sector, for wind power, hydropower and moisture recycling (Rios-Entenza et al. 2014 [80].

For this study, WRF was setup with two grids, a parent one at 27 km (WRF27km) and a second nested at 9 km (WRF9km) horizontal grid spacing, using one-way nesting. Both grids are centred in the Iberian Peninsula and have, respectively, 162x135 and 144x111 grid points, covering the regions shown in Figure 3.1. In both domains 49 vertical levels are used, placing roughly 20 vertical levels in the planetary boundary layer, with the lowest model sigma level at approximately 10 m of height and model top at 50hPa. The outermost domain was designed to cover a relatively large ocean area, reducing spurious boundary effects in the inner region. The WRF model run was set to start at 0000UTC (Universal Time Coordinated) 1 January 1989 and end at 2300UTC 31 December 2007. Initial and lateral conditions for the outer domain were derived from the ERA-Interim pressure-level reanalysis (Berrisford et al. 2009) [55]. The lateral boundary conditions and sea surface temperatures were both updated every 6 hours, from ERA-Interim. In both domains 11 grid points are used as lateral relaxation areas. A complete and more detailed description of the model set-up can be found in Soares et al. (2012) [19] and Cardoso et al. (2013) [20], where the simulation results were extensively validated for inland maximum and minimum temperatures and precipitation, showing a remarkable agreement with either local or gridded observations. This simulation is one of the most valuable climate dataset at high resolution for Iberia, containing hourly data for numerous meteorological variables. For the present study, the variables used are: surface temperature (2m), specific humidity (2m) and surface atmospheric pressure. For all these variables the hourly sampling was used to compute the CCP, direct and evaporative.

3.4. Results and discussion

3.4.1. Direct Ventilation Vs Evaporative Cooling

In this section, the methodology presented previously (section 3.2) is applied for direct ventilation and evaporative cooling, and CCP is mapped for the IP over 21870 locations. The rate of ventilation for the passive systems and reference cases (v and v_{ref} of equation 3.1) are set at 1.5ach. However, a sensitivity analysis to the air flow rate is conducted at section 3.4. Figure 3.1 and 3.2 show the monthly average values of the CCP for direct ventilation and evaporative cooling, as well as standard deviation over the 1989-2008 period. The CCP is given in kWh/m^3 (kWh per m^3 of ventilated building).

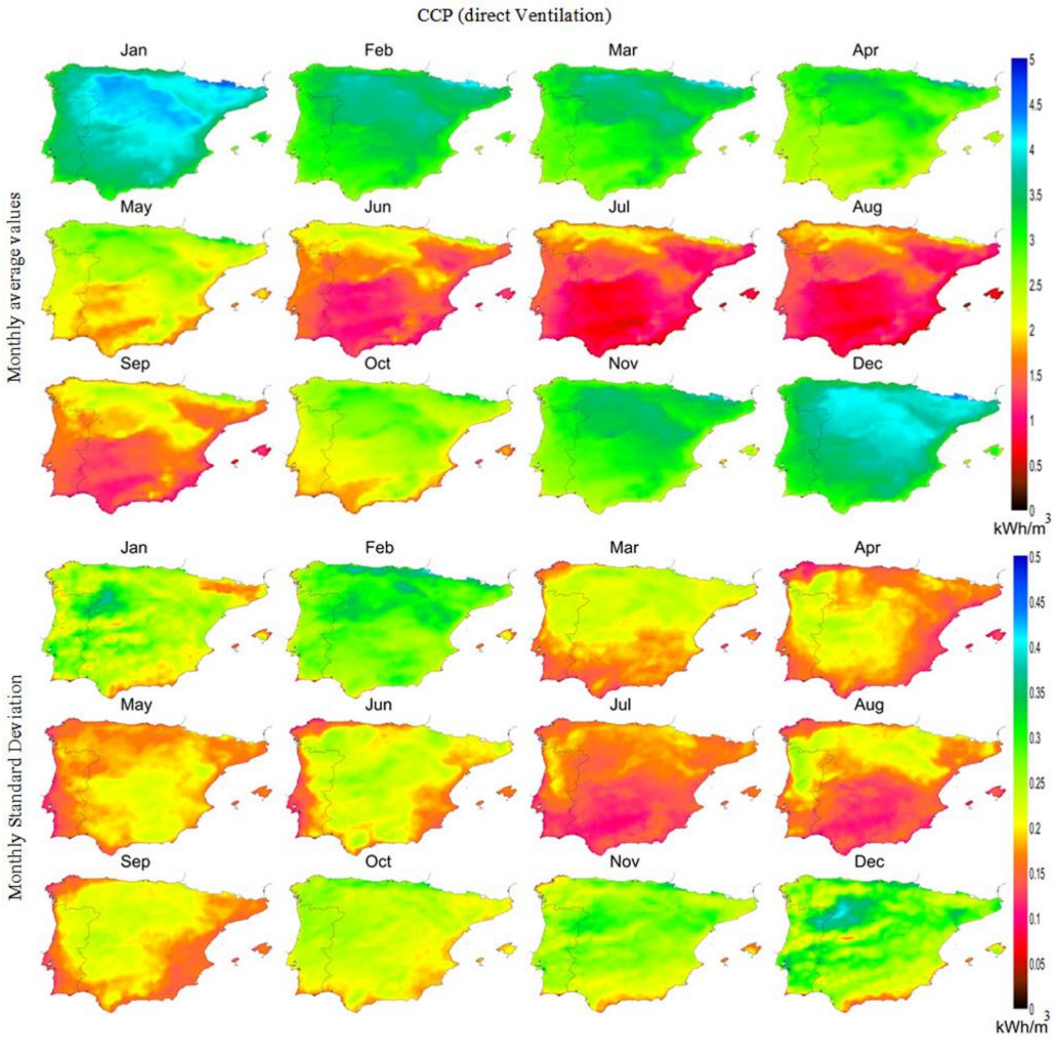

Figure 3.1. Direct Ventilation´s CCP for reference and passive rates of ventilation of 1.5ach. Top: CCP´s monthly average values; Bottom: CCP´s monthly standard deviation, for the period 1989-2008.

Regarding direct ventilation, Figure 3.1 shows that CCP is generally above 2.5 kWh/m^3 in winter (October to March) over the entire IP, reaching 4kWh/m^3 in the Pyrenees and the Iberian Cordillera from November to March. However, during summer, where the CCP is of higher utility, these values tend to diminish. At the beginning of the summer the average CCP is of 2.0kWh/m^3 falling to 1.3kWh/m^3 when considering all summer (April to September). The spatial heterogeneity of CCP is also evident in Figure 3.1, showing higher CCP values in the north part of the IP (generally above 1.5kWh/m^3 during all summer) and lower values in the south part, mostly bellow 1kWh/m^3, with the exception of April and May due to lower temperatures. The IP´s orography seems to have a significant effect in CCP, particularly in summer: the low altitude regions, as the Guadalquivir and the Ebro basins present lower CCP values, normally bellow 1kWh/m^3, contrary to the high altitude regions, like the Pyrenees and the Iberian Cordillera where CCP is higher, usually above 2kWh/m^3. Moreover, CCP tends to be lower at the southeast coastal regions of the IP due to higher temperatures of the Atlantic and the Mediterranean Sea during this same period. The standard deviation values of Figure 3.1 (bottom) show a distinct spatial heterogeneity over the entire year and a trend for lower values during summer, where the standard deviation maximums are near 0.3kWh/m^3 with an average of 0.14kWh/m^3. For this period, the standard deviation represents a maximum of 11% relatively to the average CCP.

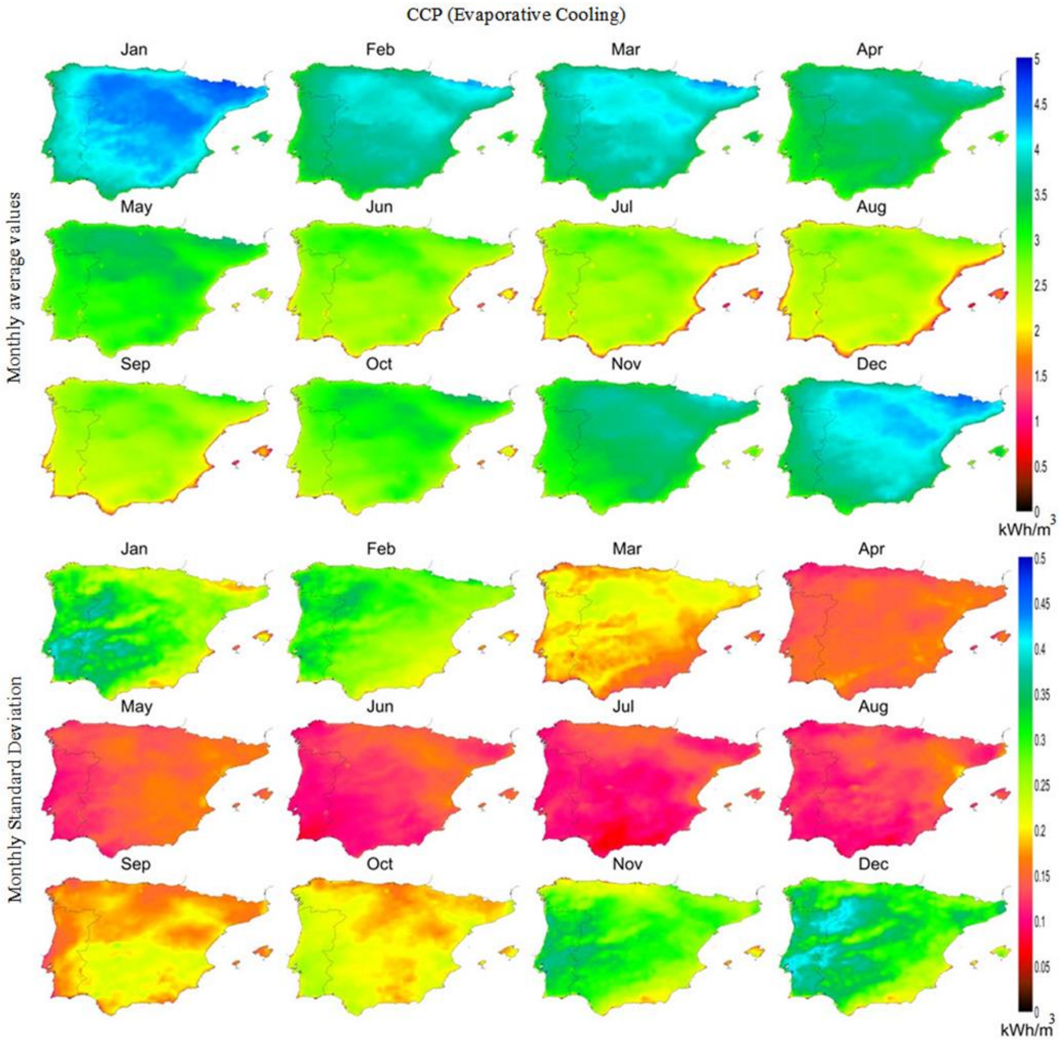

Figure 3.2. Evaporative Cooling´s CCP for reference and passive rates of ventilation of 1.5ach. Top: CCP´s monthly average values; Bottom: CCP´s monthly standard deviation, for the period 1989-2008.

Concerning evaporative cooling, a similar picture can be found (Figure 3.2). Like direct ventilation, during winter, where the temperatures are lower, CCP is higher, generally above 3kWh/m^3 over all the IP. However, in this case, the CCP´s spatial homogeneity is clearly higher during all year. Moreover, with the exception of the southeast coast, the average inter-annual amplitude of the evaporative cooling´s CCP is near 2.5kWh/m^3, instead of 4.5kWh/m^3 (case of direct ventilation). Furthermore, for the majority of summer (June to September) the CCP´s spatial distribution along the IP as well as its average is quite similar from month to month, with most of its values above 2.0kWh/m^3. Contrary to direct ventilation, where the IP´s orography influence in CCP is more pronounced, in the case of evaporative cooling, the regions of the Guadalquivir and the Ebro´s basins do not show substantially lower CCP during summer. Similarly, the regions of higher altitudes such as the Pyrenees and the Iberian Cordillera do not present noticeably higher CCP values relatively to other regions. Nonetheless, for the evaporative cooling there is a more distinct coastal effect, i.e. the proximity to the Ocean causes evaporative cooling´s CCP to be substantially lower on southeast coast due to higher moist in air. This effect, combined with the warmer currents of the Atlantic and Mediterranean sea, causes the lower CCP values displayed during summer in the southeast coast of Figure 3.2 (~1.5kWh/m^3). Nevertheless, for the same periods and locations, evaporative cooling provides consistently higher CCP values than direct ventilation (see Figure 3.3). One of the reasons is due to the duration during which CCP is available: Figures 3.1 and 3.2 were produced with equal design and reference flow rates (v_{vnt} and v_{ref}), hence the CCP for direct ventilation is only available at night, when ventilation from outdoor can continue as compared to the reference case. For evaporative cooling, the ventilation temperature is lower than ambient, therefore the cooling potential (as compared with the reference) doesn’t drop to zero during day time.

In order to better access the difference between evaporative cooling and direct ventilation, Figure 3.3, expresses the relative difference between the CCP from evaporative cooling and direct ventilation.

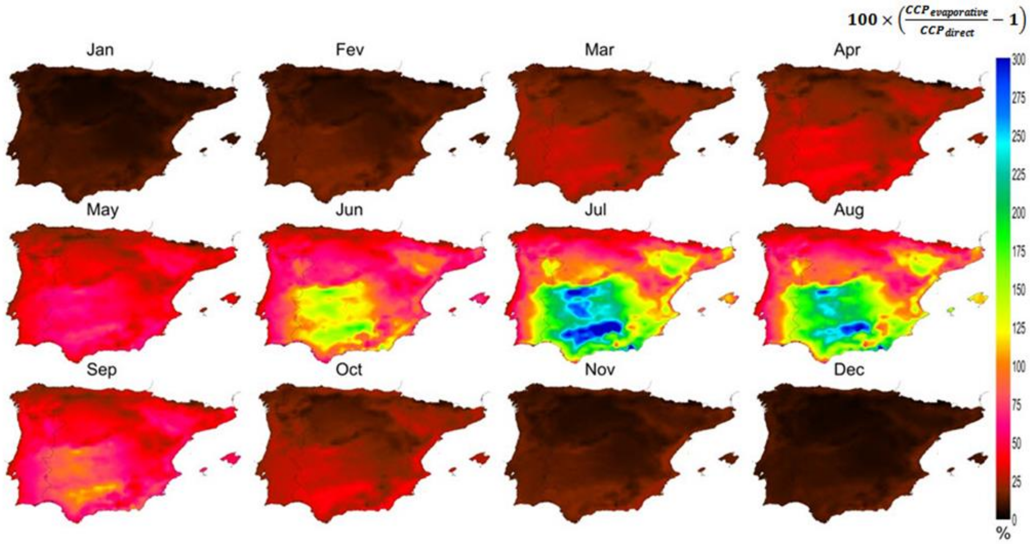

Figure 3.3. Relative difference (%) between CCP for evaporative cooling and direct ventilation for 1.5ach reference and passive rates of ventilation

During the winter the relative difference between the systems is between 2% and 69% with an average of 14%. However, during the summer, the discrepancy between the systems increases importantly. For the warmest months, in the climatological summer (June to August), the relative difference between evaporative cooling and direct ventilation is usually above 50%, furthermore, at the south central part of the IP the evaporative cooling system may provide 100% more CCP than direct ventilation, reaching local values above 250%. Nevertheless, for some regions, predominantly in the coast, due to high levels of air ocean moisture, the difference can be inferior to 11% in the full annual cycle.

Figure 3.4 shows the mean monthly values of the relative difference of Figure 3.3, for two specific illustrative locations, one in the coast (Mañón, Bares, Spain: 43º44’22” N; 7º42’35” W) and the other in the interior of the IP (Castelo Branco, Portugal: 39º48’39” N; 7º30’28” W).

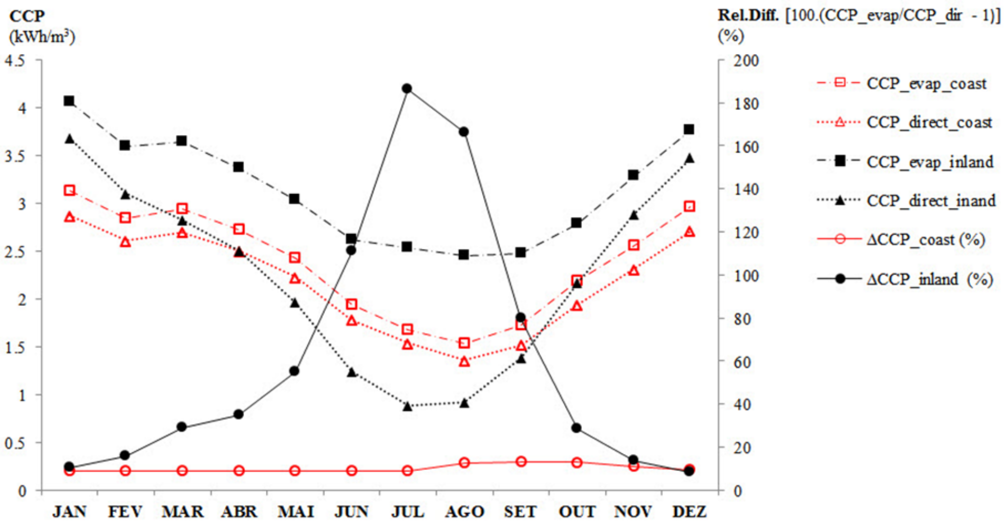

Figure 3.4. Relative difference (%) between CCP for evaporative cooling and direct ventilation for 1.5ach reference and passive rates of ventilation for a region in the coastline and in the inland of the IP

It can be seen that there is very significant difference in using evaporative cooling in relation to direct ventilation between a coastal location and an inland one. The annual cycle of improvement using evaporative cooling in a coastal location presents a small average value mostly constant, around 10%, i.e. with reduced amplitude, in the range between 9 and 13%, in May and September, respectively. The inland location, however, shows an average value of relative difference 50% higher for the full year. More importantly, during the summer the discrepancy between the two locations is remarkable, the average value is 95% larger, but the annual amplitude is also more noticeable due to the proximity between the inland and coastal ratios during winter, where evaporative cooling tends to be less effective relatively to direct ventilation.

3.4.2. Sensitivity to air flow rate

In the previous section the rate of ventilation was set at 1.5ach for the reference rate and for the passive cooling systems, however higher rates of ventilation can be used. To understand the effect of increasing the rate of ventilation, we conduct a sensitivity analysis for 3.0ach and 6ach air flow rates for both passive cooling systems. The reference rate of ventilation (v_{ref}) is kept at 1.5ach. The CCP spatial structure (not shown here) is similar to the ones presented on Figure 3.1 and 3.2. To illustrate the scale factors between the different flow rates, the ratio between the CCP for 3.0ach and 1.5ach, as well as for 6.0ach and 1.5ach was computed for each IP grid point (near 22000 locations) for direct ventilation and evaporative cooling. As a summary, the different statistical measures of these ratios, namely the absolute extremes, quartiles, median, average and standard deviation are calculated for monthly values for both systems, for the full meteorological model database (Figures 3.5 and 3.6).

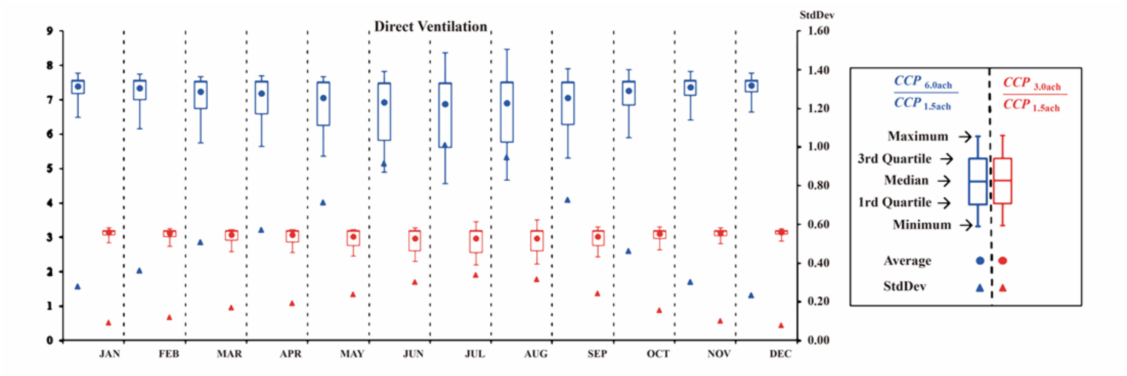

Figure 3.5. Spatial statistics of CCP for direct ventilation: ratio between CCP for 6.0 and 1.5 ach (blue) and between CCP for 3.0 and 1.5 ach (red).

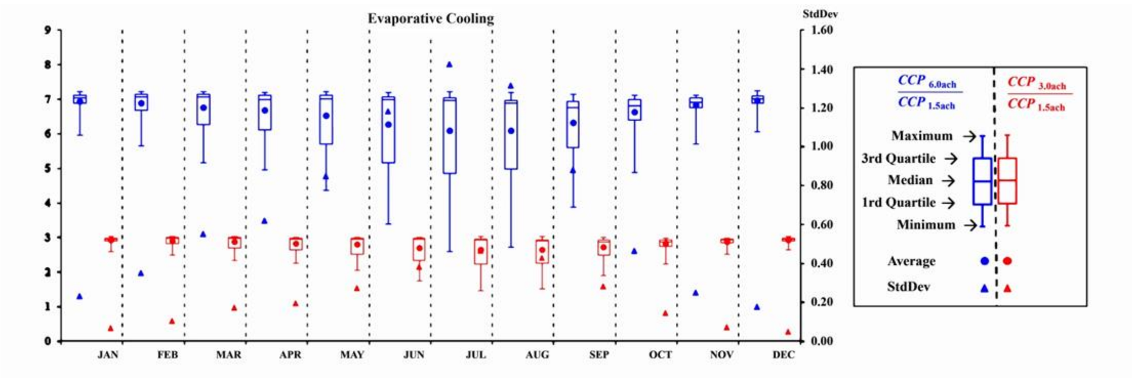

Figure 3.6. Spatial statistics of CCP for evaporative cooling: ratio between CCP for 6.0 and 1.5 ach (blue) and between CCP for 3.0 and 1.5 ach (red).

In the case of direct ventilation, Figure 3.5 shows clearly the non-linear gain of using higher ventilation rates (see equation 3.1). Doubling and quadruplicating the ventilation rates leads to an annual average ratio´s increase of 3.1 and 7.2, respectively. In fact, for the 3.0/1.5ach ratio of direct ventilation, the monthly average values in the annual cycle are roughly constant, with an annual average equal to 3.1, reaching a maximum of 3.5 in August and a minimum of 2.2 in July. The monthly range of the sample varies from 0.37 in December to 1.29 in August. Standard deviation achieves its minimum of 0.08 in December and its maximum of 0.34 in July, which represents only 11% of the average value for the same month. For the 6.0/1.5ach ratio the annual average is 7.2 and the monthly ranges of the sample are wider, varying form 1.1 in December to 3.8 in August. The standard deviation values are also higher, ranging from 0.23 in December to 1.01 in July, however, the maximum relative difference from the monthly average is only of 15% (for July). Also, a greater interquartile distance is visible in the summer, which causes standard deviation vales to be higher.

For the 3.0ach /1.5ach ratio of the evaporative cooling case (Figure 3.6) the monthly ranges are similar to direct ventilation but with greater standard deviation values, between 0.06 (December) and 0.48 (July), however, in the case of the 6.0/1.5ach ratio the monthly ranges are higher, varying from 1.2 in December to 4.7 in July, as well as the standard deviation, which varies from 0.19 in December to 1.4 in July.

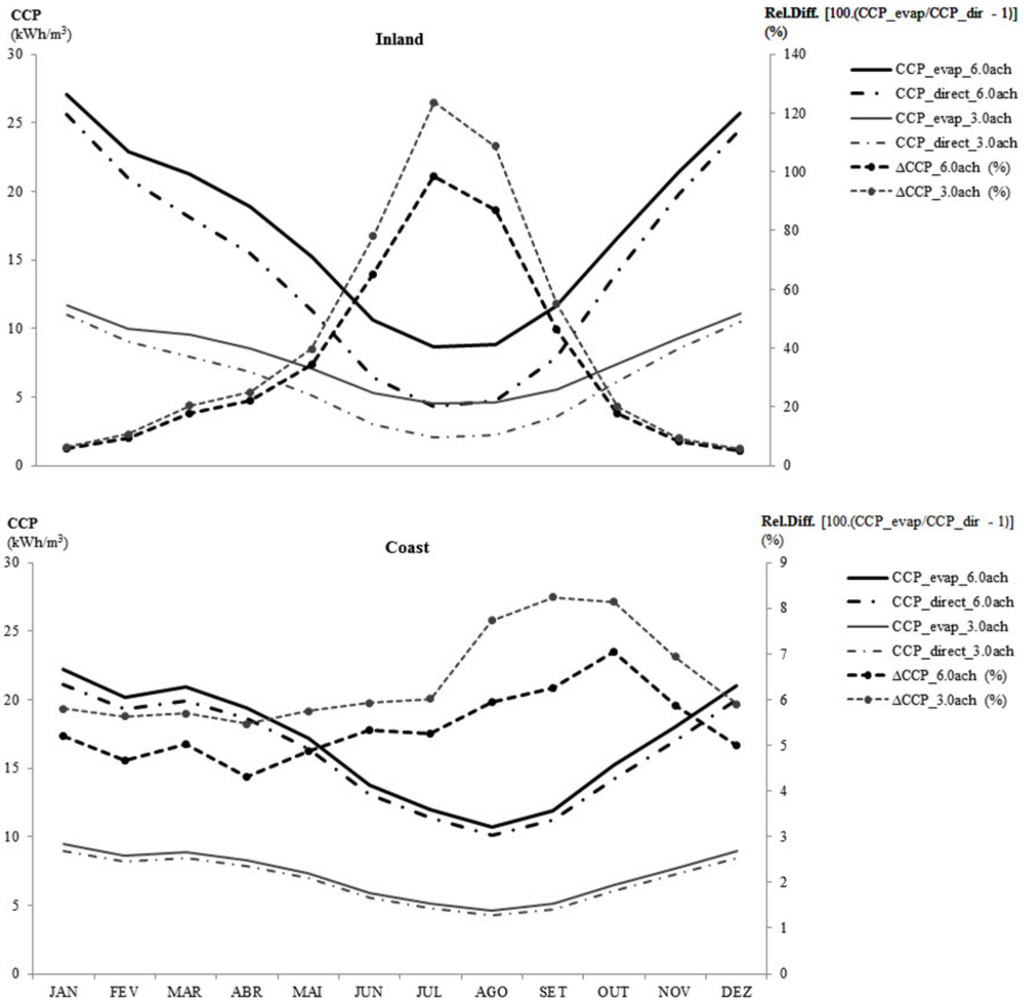

Figure 3.7. CCP (left axis) and CCP´s relative difference between evaporative cooling and direct ventilation (right axis) in an inland (top) and a coastal region (bottom) for different rates of ventilation.

In Figure 3.7 the relative difference from evaporative cooling and direct ventilation is displayed for the same inland and coastal locations of Figure 3.4, for 3.0ach and 6.0ach passive flow rates along the full annual cycle. The relative difference between evaporative cooling and direct ventilation diminishes with the increased air flow rate of the passive systems. This decrease is more pronounced when comparing the 3.0ach and 1.5ach air flows than the reduction from 6.0ach to 3ach, since at 1.5ach there are some periods when the direct ventilation corresponds to the reference flow rate.

3.4.3. Assessing Useful Cooling Potential

In order to assess the UCP for a specific building one needs to know its cooling demand and volume. As an example, here we proceed to thermal simulation of two office rooms (undermentioned as "A" and "B") located in the region of Lisbon using TRNSYS [50]. The office rooms are $20m^2$, $50m^3$, south orientated, with $20W/m^2$ internal gains. The air renovation flow rate is of 1.5ach during occupation (7h – 19h). Building "A" has 50% glazing area without any kind of solar protection (overall g value of 68%), while building "B" has 50% glazing with exterior solar protection (activated when direct radiation on the façade exceeds 10 W/m^2: overall g-value of 13%). The simulation was conducted for the month of August yielding a cooling demand of 183kWh ($3.7kWh/m^3$, $9.1kWh/m^2$) for building "A" and 66kWh ($1.3kWh/m^3$, $3.3kWh/m^2$) for building "B".

Checking the top panel of figures 3.1 and 3.2 (for direct ventilation and evaporative cooling, respectively) in the region of Lisbon, it can be seen that CCP is between $1kWh/m^3$ and 1.5kWh/m3 for direct ventilation and between $1.5kWh/m^3$ and $2kWh/m^3$ for evaporative cooling.

Thus, for building "A", direct ventilation can offer a cooling demand saving between 27% and 40%, and evaporative cooling between 40% and 54%. For the case of building "B", direct ventilation can offer a cooling demand saving between 76% and 100%, and the expected savings for the evaporative cooling system is of 100%. Nevertheless, it is important to note that the exclusive use of solar protection can bring the cooling demand down by 64% which is more than direct ventilation or evaporative cooling can offer for the selected air flow.

To assess the CCP for different rates of ventilation one can use the method above along with figures 3.5 and 3.6. For building "A", inspecting figure 3.5, it can be seen that for 3.0ach direct ventilation´s air flow rate, the CCP value in the month of August is 2.2 to 3.5 times higher than the CCP value for 1.5ach, which results in 59% to 100% cooling demand savings. For the case of an air flow rate of 6.0ach, the expected UCP is at least 4.7 times higher than the UCP for 1.5ach, resulting in 100% cooling demand savings. For the case of evaporative cooling, the 3.0ach air flow results in a CCP´s increase from 1.6

to 3.1times, this implies an increase from 64% to 100% in cooling demand savings. For the case of a 6.0ach air flow, the expected increase in cooling demand savings is of 100%.

3.5. Conclusions

In the present paper we propose a new methodology to compute the cooling demand savings for any ventilated passive cooling system for any building and spatiotemporal scale. Here, this methodology is performed for two passive cooling systems, direct ventilation and evaporative cooling, for different air flow rates and using a high quality climate dataset regarding the Iberian Peninsula. The latter was produced using a state-of-the art regional climate model, at 9km resolution for a 19 years period, with hourly data output. We apply this procedure to the Iberian Peninsula, and thoroughly explore the benefits and caveats of both systems, comparing their potentials and their sensitivity to air flow rates. The approach is based on the calculation of the climate cooling potential and its relation with the building cooling demand.

The monthly values of the climatic cooling potential are temporally and spatially heterogeneous both for direct ventilation and evaporative cooling. Evaporative cooling always provides greater potential for the same time periods no matter the location in the Iberian Peninsula.

There is a clear asymmetry between the northern and southern part of the Iberian Peninsula regarding the potential for both direct ventilation and evaporative cooling, with higher potential values in the northern part.

Evaporative cooling provides a less heterogeneous annual cycle of climatic cooling potential, except for the areas confined to the coast and the semi-arid regions. Generally, evaporative cooling provides greater potential values than direct ventilation, but this property lessens during the winter and increases during summer, when the potential is of greater interest. Nevertheless, in some coastal regions, evaporative cooling provides less than 10% rise on the climatic cooling potential compared to direct ventilation.

The relation between the CCP provided by the different systems is of great importance for trying to understand the best system to implement in a given region, both from efficiency and economic stand points. Evaporative cooling systems have higher investment and maintenance costs. Obviously, the gain associated to evaporative compared to direct ventilation has to compensate the investment and maintenance costs. For both systems a nonlinear behaviour is found between the climatic cooling potential and the air flow rate.

Finally, the innovating methodology presented can be applied for any observational dataset or RCMs results, permitting the assessment of the climate change impact on the different passive cooling systems, and on the strategic decisions concerning their implementation, and therefore boosting the use of the renewable energy resources as a direct source of clean energy to be used in the greatest energy consuming sector, the sector of buildings: one can easily use the present study for a estimation of cooling demand savings provided by an evaporative cooling and/or a direct ventilation system in any building located in the IP, which in turn, will serve as an incentive for the implementation of such a systems in a simplified way, without the need for a complex analysis or to master thermal simulation tools, which require expertise, are a time consuming process, and require solid knowledge on the passive systems, slowing down the process of implementation and increase its costs.

4. Impact of climate change on building cooling potential of direct ventilation and evaporative cooling: a high resolution view for the Iberian Peninsula

Abstract

The current study uses a new methodology where the assessment of building cooling demand savings is obtained through a redefined concept of the Climatic Cooling Potential (CCP). This concept allows for the direct estimation of energy savings in buildings by the use of different passive cooling systems at a large spatiotemporal scale. In this paper, we apply this method to assess the impact of climate change on the future potential of Direct Ventilation and Evaporative Cooling. To do so, a set of high resolution climate simulations for the Iberian Peninsula for present and future climate, performed using the Weather Research and Forecasting model (WRF), were used. Three passive cooling simulations were conducted: the first one employs the hindcast simulation where WRF is forced by the reanalysis ERA-Interim for the 1989-1999 period (hindcast); the second employs the EC-EARTH forced historical run ranging from 1970 to 2000 (historical) and the third also forced EC-EARTH but for 2070 to 2100 (future). An eleven year period was extracted from the historical run and validated against the first, the hindcast. The similitude of the results provided confidence on the ability of the EC-EARTH forced runs to correctly simulate climate and thus allowing the assessment of the effect of climate change in the outcome of the passive systems and cooling demand savings in buildings. The results show that CCP conserves its spatial heterogeneity for both historical and future, but presents lower values for the future due to the increase in temperatures. Nevertheless, this reduction is mostly below 20% over the entire Iberian Peninsula along the annual cycle, for both Direct Ventilation and Evaporative Cooling. This means that even in the context of a changing climate, these kind of systems can still offer valuable reductions on the cooling demand of buildings. Furthermore, most of the reductions in the CCP, caused by the increase in temperatures, can be surpassed by increasing the flow rate or can even be compensated by the increase in Cooling Demand as a consequence of the rising temperatures.

Keywords: climate change; passive cooling; climatic cooling potential; Iberian Peninsula; renewable energy resources

Nomenclature

Abbreviations

ach	air changes per hour (h-1)
CDH	Cooling Degree Hours (Kh)
CCP	Climatic cooling potential (kWh per m^3 of ventilated building)
GCM	Global Climate Model
RCM	Regional Climate Model
RCP	Representative Concentration Pathway scenarios
UCP	Useful cooling potential (kWh per m3 of ventilated building)
WRF	Weather Research and Forecasting model

Symbols

c	heat capacity of air (kWh/K.kg)
ρ	air density (kg/m3)
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 (ºC)
T_{vnt}	passive cooling system output temperature (ºC)
T_{set}	building´s set point temperature (ºC)
T_{ext}	outdoor temperature (ºC)
UCP	useful cooling potential (kWh/m3 of ventilated building)

Q_{cool}	building´s cooling load (kWh)
η	evaporative cooling system´s efficiency
T_{wb}	wet bulb temperature (ºC)

4.1.Introduction

Climate change is seen as one of the highest challenges that present humankind faces. Climate change is not regarded anymore as only an environmental problem but an issue with impacts at all economic and societal levels, especially in the energy sector [81]. Climate change and the shortage of oil are the main drivers for the expansion of renewable energies worldwide, particularly in Europe. Energy systems, although being one of the key systems for social and economic development, often do not comprise the effects of a changing climate in their planning and operation [82]. The latter authors stress that climate impact assessments on energy planning and operation need to take into account a higher number of scenarios, as well as investigate impacts on particular energy segments.

In 2014 buildings were responsible for nearly 40% of the final energy consumption in Europe [83], placing the building sector as the biggest energetic consumer, above industry (31%) and transportation (26%) [51]. The rapid increase in electricity demand for air-conditioning of buildings associated with global warming will further boost the primary energy demand for building cooling [23-26], and will greatly increase the need for passive cooling systems. These systems make use of naturally available heat sinks, closely related to local meteorological properties, like temperature and humidity. Among these techniques, an important role goes for systems that use the building’s ventilation system to activate the available cooling resource and distribute it [28], e.g.: a) direct night ventilation, b) buried pipe systems, c) controlled thermal phase-shifting, d) evaporative cooling. From these techniques the ones most widely used are direct ventilation and evaporative cooling due to their simplicity. Passive cooling systems can also be classified as renewable energy resources, since they use the natural available heat sources/sinks [84]. This study is focused in direct ventilation and evaporative cooling.

Direct ventilation can be used whenever there is cooling demand inside a building and the outside temperatures are lower than the building´s set point temperature. In this case, outside air can be transported inside the building decreasing its temperature and the cooling load. The air can flow driven by thermal gradient forces through openings (natural), using fans (mechanically forced), or both ways [13]. Direct ventilation is frequently used during night and therefore designated as night cooling. The efficiency of direct ventilation depends on the difference between indoor and outdoor temperatures, the air flow rate, the building´s thermal mass and the cooling demand [27]. Direct ventilation can be very efficient in the reduction of the cooling loads [29- 31].

Evaporative cooling uses the principle of water evaporation for heat absorbing, and can be direct or indirect. In direct evaporative cooling the humidified air is transported directly into the building. To avoid condensation inside the building, the air can be forced through a membrane for a previous separation of the water vapour [85]. In indirect evaporative cooling, the cooled humidified air is forced into a heat exchanger, decreasing its temperature while maintaining the indoor humidity, lowering the risk of condensation [37]. In the last decades, evaporative cooling has seen its use increase, mostly in air conditioning, owing to its simplicity in structure and use of natural energy in the form of latent heat of water [86, 87]. Evaporative cooling is used extensively for cooling in climates with medium to low humidity [88], and has proven its economic and technical feasibility through several studies [33-36]. It is expected that indirect evaporative cooling systems will represent around 20% of air-conditioned market in buildings over the next 20 years world-wide [37].

The implementation of passive cooling systems should normally require a case by case viability assessment, using building thermal simulation or in situ measurements, which are inaccessible for most of the building designers. Therefore, the selection of these techniques is rarely based on a thorough assessment of its potential, either in the case of direct or indirect evaporative cooling. Nevertheless, only a rather small number of investigations tried to grasp, in a systematic way, the characterization of the regional cooling potential. However some examples exist where the potential of specific passive cooling techniques at European level were performed, namely, [13] for direct night ventilation and [33] for evaporative cooling.

Artman et al. [13] proposed the Climatic Cooling Potential (CCP) index which is the average number of nights of the accumulated nightly hourly indoor and outdoor temperature differences whenever this difference is above 3 K. The CCP gives a measure of the climatic availability for direct cooling ventilation. In Campaniço et al. [89], this index was further developed and generalized to incorporate humidity, in a way that it can be also used to describe the climatic evaporative cooling [53, 89]. These authors also developed the concept of the Useful cooling potential (UCP) allowing a direct estimate of the cooling demand savings in buildings by the use of several ventilated passive cooling systems (direct ventilation, evaporative cooling, buried pipes, phase-shifter) without the need for building thermal simulations and independent of the building properties [53]. Furthermore, for the first time, Campaniço et al. [89] mapped the climatic cooling potential for present climate, for both direct ventilation and evaporative cooling, using regional climate model results for Iberia. Their results reveal that within Iberia the CCP is asymmetrically distributed both spatially and temporally. During the cooling season (May to September), CCP values are generally above 1kWh and 3kWh per m3 of building, for direct ventilation and evaporative cooling, respectively. Evaporative cooling shows consistently higher values than direct ventilation, but in the coastal regions the relative difference between the two systems drops to less than 10%. For 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 correspond to more than 27% and 40% of the cooling demand, respectively.

Passive cooling systems strongly rely, by its nature, on the climatic thermal resource, or in another way, on local climate. Therefore, it is crucial to assess at the regional and local scales how climate change will impact on the climate cooling potential, and subsequently address the changes on its economic viability. In fact, the number of studies integrating the impacts of climate change on the use of passive cooling systems, and in general building thermal behaviour, is very scarce. Hanby and Smith [15] simulated the future performance of low-energy evaporative cooling systems using UKCP09 climate projections and pointed out to higher potential for the application of evaporative cooling for the UK. Gupta and Gregg [90], also for the UK, analysed an ensemble of adaptation measures for existing English homes in the context of a warming climate, concluding that among several passive cooling systems none could eliminate the overheating in the homes by 2080. Frank [91] used a climatic future scenario for Zurich–Kloten (2050–2100) to perform transient building energy simulations and investigate the potential influence of climate change on heating and cooling energy demand, but this study does not include the impact on possible passive cooling techniques. Recent studies [92-94] stress the impact of climate change on the increase of buildings cooling demand but establish no relation with passive cooling techniques efficiency on a warming climate. An exception is the work of Seyed M. S. et al. [95] where the climate change effect is considered in the dimensioning of Phase Change Materials to be used to reduce cooling loads. Nonetheless, this study is applied to a specific type of building using thermal simulation, and therefore does not provide general information on the effectiveness of the passive cooling systems at a large spatiotemporal scale neither in a way expandable to any build type.

In another study by Campaniço et al. [53] where the concept of the CCP was firstly developed independent of building properties, the UCP was tested against the effective cooling demand savings data for an extensive numerical simulation campaign comprising 7776 configurations for an administrative building located in Geneva, Switzerland (including direct ventilation, evaporative cooling, air-soil heat exchangers, thermal phase-shifting, as well as combination thereof, with diverse sizing and flow rates). The authors show that calculation of the UCP on an hourly basis underestimates the effective savings by an average of 31%, due to the fact that the building thermal inertia is not taken into account, while calculation of the UPC on a daily basis reproduces the effective savings with less than 1% error in average. On the basis of the aforementioned results, Campaniço et al. [89] established a CCP database for the Iberian Peninsula (IP), on monthly basis, concerning direct ventilation and evaporative cooling for the present climate.

The present study makes use of Regional climate models (RCMs). RCMs have the ability to capture physically consistent regional and local circulations, as so, they have become an increasingly sophisticated tool for the development of high-resolution climatologies, for present and future climate [50, 96-99]. The synchronized present climate simulation (hindcast), of this set of simulations, was also used to characterize the climatic cooling potential of direct ventilation and evaporative cooling for Iberia [89]. The extension of this latter study, in the context of a warming climate, is precisely the fundamental aim of the present study.

Thus, we propose to assess the climate change impact on the climatic cooling potential and the energy savings, for direct ventilation and evaporative cooling, in Iberian Peninsula. To accomplish this objective a detailed comparison between present and future climate cooling properties is presented, and a thorough analysis of the expected changes associated with global warming is performed, reproducing a first and unique dataset giving an insight on the sustainability of direct ventilation and evaporative cooling at a large spatiotemporal scale for the future climate.

In section 4.2 the methods are described. Section 4.3 provides a comparison between EC-EARTH (control) and ERA-Interim (hindcast) for the same time period. In section 4.4, the two EC-EARTH forced model simulations, historical (1971-2000) and Future (2071-2100) are used to assess the climate change effect on CCP. Finally, in section 4.5, the main conclusions are drawn.

4.2.Methodology and data

4.2.1. Methods

The method used in the present study follows closely Campaniço et al. [89]. In this study, CCP is defined in a way that allows for the assessment of the cooling demand savings provided by the use different passive cooling systems in buildings for any spatiotemporal scale. CCP expresses the difference between the amount of thermal energy that is removed from a building (cooling) by a given ventilated passive cooling system in a given hour, and the amount of thermal energy that is being removed or flowing into the same building (depending on the air´s flow temperature in relation to the building´s temperature) via the reference flow rate (air renovation) at the same time step:

$$CCP = c \cdot \rho \cdot v \cdot (T_{bld} - T_{vnt}) - c \cdot \rho \cdot v_{ref}(T_{bld} - T_{ext})$$

$$v = \begin{cases} v_{vnt} & if \;\; T_{vnt} < T_{bld} \\ v_{ref} & if \;\; T_{vnt} \geq T_{bld} \end{cases} \qquad \text{(Eq. 4.1)}$$

In equation 4.1, "*CCP*" is the Climatic Cooling Potential in kW per m^3 building (or kWh per m^3 building when integrated over a certain period), "c" is the heat capacity of air (kWh/K.kg), "ρ" is the air density (kg/m^3), "v" is the air flow rate in air exanges per hour, "T_{vnt}" is the ventilation temperature (K), "T_{bld}" is the temperature inside the building (K) and "Text" is the air outside temperature (K).

The system may be designed at a higher flow rate (v_{vnt}) than the standard flow rate (v_{ref}), enhancing the cooling load, but should be reduced to (v_{ref}) when the source temperature is higher than the building. Furthermore, the flow rates must be building specific (air changes per hour), so that the CCP is expressed in kW per m^3 building (or kWh per m^3 building when integrated over a certain period).

Since there is no prior knowledge of the building temperature, CCP is evaluated for a comfort set point temperature T_{set} (instead of T_{bld}) and therefore it represents a climatic index which is independent of any building characteristics, depending only on the climate under consideration, the passive cooling system and its flow rate, as well as the comfort set point.

At certain days, e.g. often in winter and in cool nights during the other seasons, CCP might be higher than the actual cooling load of the building, meaning that for the assessment of its effective contribution, in terms of thermal energy savings for a particular building, CCP must be compared to the cooling load Q_{cool} in absence of passive cooling, i.e. the amount of cooling which is needed for the building temperature not to rise above T_{set}. This comparison is done over a certain integration time step allowing for the reduction of the CCP to the Useful Cooling Potential (UCP) of the particular building.

For the case of direct ventilation, "T_{vn}t" of equation 4.1 is simply given by the dry bulb ambient air temperature, (T_{vnt} = T_{ext}), while evaporative cooling is simulated with a constant efficiency η of 50% (in relation to the wet bulb temperature T_{wb}):

$$T_{vnt} = T_{ext} + \eta(T_{wb} - T_{ext}) \quad \text{(Eq.4.2)}$$

On the basis of equation (4.1) the CCP will be computed for the case of a comfort set point "T_{set}" of 26°C, with a reference flow rate "v_{ref} " of 1.5 ach (of 1.5 m^3/h per m^3 building) during daytime (7h – 19h), dropping to zero during the night (representative of an administrative building). The passive cooling system will be assessed for 2 different design flow rates "v_{vnt}" : (i) 1.5 ach (same as the reference case, but also activated at night if T_{vnt} is below T_{set}); (ii) 6.0 ach (reduced to reference if T_{vnt} is higher than T_{set}).

The comparison of CCP for present and future climates enables the characterization of the impact of global warming for each of the passive cooling systems considered.

The climatic input is described in the next sub-section.

4.2.2. Climate Data: WRF high resolution simulations

In the present study, we use a set of high resolution, regional climate simulations for Iberia using the Weather Research and Forecasting model (WRF) [17] at 9km resolution. The set of simulations correspond to two domains, one larger at 27km resolution, and a nested higher resolution domain at 9km, both centred on the Iberian Peninsula (Figure 4.1) with 144x111 and 162x135 grid points, respectively. A comprehensive description of the model set-up and parametrisations used can be seen in Soares et al. [19] and Cardoso et al. [20]. Three simulations were performed: one hindcast simulation with boundary conditions provided the ERA-Interim reanalysis [18] for the period 1989-1999, and two climate simulations with boundary conditions from the EC-EARTH global climate model [100]; a historical run for 1970-2000 (historical) and a future run for 2070-2100 (future). The hindcast simulation is a synchronized simulation, so it can be directly compared with observations [19-21,101] and the other two are not synchronized, and so only their statistics can be compared. The hindcast results were used and evaluated in diverse studies, from precipitation properties, spatial and temporal distributions of Portuguese temperature [19;20], moisture recycling processes [102], coastal surface wind and low-level jets [101], Iberian solar resources [21], clouds [103] and wildfire propagation models [104, 105]. The historical and future results have also been used in several studies related to precipitation [106], temperature [107], wind [108, 109] and solar radiation [110].

4.2.3. Cooling Degree Hours

Cooling Degree Hours (CDH) are related to buildings' cooling demand. In principle, the greater the CDH, greater the cooling demand, however, this is not a linear relation since many factors (such as insulation, internal gains, solar exposure, etc.) affect cooling needs [111, 112]. Nonetheless, in this analysis, for which internal gains are not taken into account and which will be focused in a climatic data set where solar radiation is not significantly changed (from historical to future climate) [110], the gradient between hourly building set point and outside temperature is the greatest impact factor in cooling demand (for a same building with the same use). Therefore, for the sake of simplicity, and since it is impossible to determine exactly how cooling demand for each building in each zone will be affected by a changing climate, we will use the concept of CDH in order to provide a rough assessment how cooling demand will change with global warming over Iberia. To do so, we will use the same climatic datasets as in previous sections, and compute the average of the sum of the differences between hourly outside temperatures and set point temperature (whenever positive) along each year in the 31 years for the historical and future climates datasets according to equation 4.3:

$$CDH = \frac{\sum_{y=1}^{31}\sum_{i=1}^{n}(T_{ext}-T_{set})^{+}}{31} \qquad \text{(Eq.4.3)}$$

In equation 4.3 *CDH* represents the yearly average for the total of Cooling Degree Hours over the whole dataset in Kh, "*n*" is the number of hours in a given year "*y*" where the condition verifies ($T_{ext} > T_{set}$).

4.3. Evaluation of the historical present climate

The propose of this section is to assess WRF's ability to produce valuable climatic data sets to compute and evaluate the CCP for direct ventilation (subsection 4.3.1) and evaporative cooling (subsection 4.3.2) for the present climate, when forced by the global climate model. To do so, we must compare the CCP computed via the climatic data input given by the hindcast simulation forced by the ERA-Interim reanalysis (hindcast) with the one forced by the EC-EARTH model historical run [100]. Since the hindcast is comprised by 11 years only, a similar period is selected from the historical run in order to perform a fair comparison (from this point forward simply this will be designated as control). Ideally, this comparison should display similar values and spatial distribution for both simulations, which would mean that control is successful in forcing WRF to produce climatic data for the end century (2070 to 2100) that can then be used to compute the CCP for the same time period.

4.3.1. Direct ventilation

CCP varies nonlinearly with air flow rate (equation 4.1), therefore, to assess the differences in CCP computed via hindcast and control, one should take different flow rates into account. The temperatures time series given by each simulation (hindcast and control) are obviously different. Once CCP is affected by the product between temperatures and flow rate (equation 4.1), the differences in CCP for the two simulations are expected to increase with flow rate. Hence, for brevity we will focus this comparative analysis on the higher flow rate of 6.0 ach that maximizes the mentioned differences. Figure 4.1 shows the monthly average CCP values over the IP for the period 1989-1999, for direct ventilation with 6.0 ach flow rate, for the hindcast and control simulations, respectively. Figure 4.1 shows a similar spatial and temporal evolution between the CCP values. To better assess the differences between CCPs, Figure 4.2 shows the average relative differences for CCP over the IP, for the period between 1989 and 1999, computed via the hindcast and control simulations for 6.0 ach rate of ventilation.

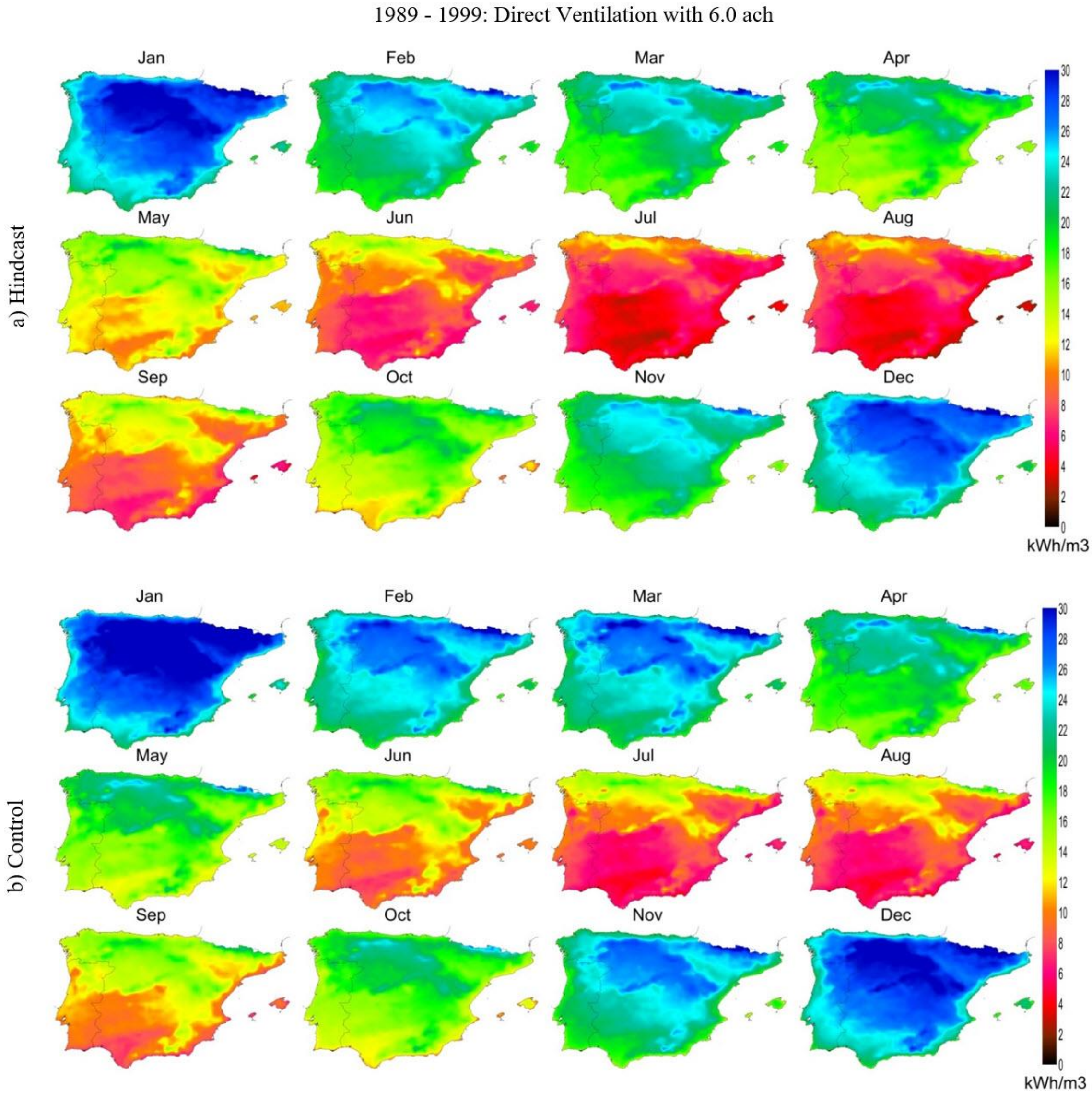

Figure 4.1. CCP Direct Ventilation, 6.0 ach (1989 to 1999), average monthly values: (a) hindcast; (b) control.

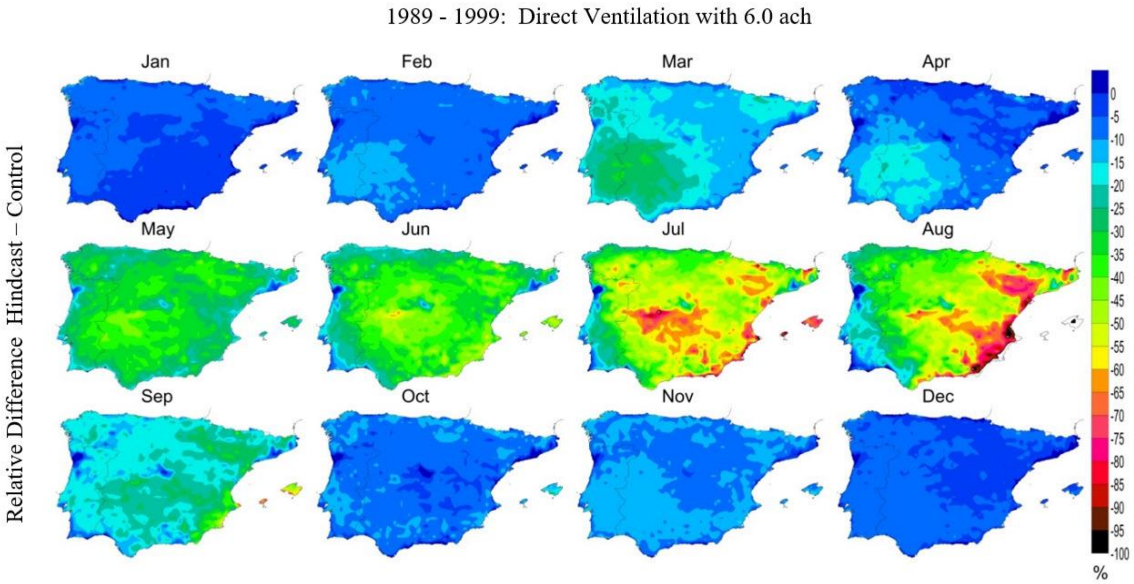

Figure 4.2. CCP Direct Ventilation, 6.0 ach (1989 to 1999), average monthly values. Relative difference between hincast and control: 100*(hindcast - control)/control.

For the cooler months (Jan to Apr and Sep to Dec), where CCP has larger values (typically over 15 kWh/m^3) due to the cooler temperatures, the differences between hindcast and control simulations remain mostly below 20%, and with large areas close to 10%, meaning that the control simulations tend to moderately overestimate CCP in relation to the hindcast simulations. For the warmer months (May to Aug), the relative differences increase, especially over the east cost of the IP. However, these are the cases where CCP has lower values, therefore a low absolute difference (like 2 kWh/m^3, which is the predominant value over the east IP´s coast for the hot months) implies higher relative differences. Overall, according to the spatial distribution of CCP from control and hindcast, and the minor deviations on its values, EC-EARTH forced model simulations are suitable to perform the assessment of the CCP for the end of the century for direct ventilation.

For the cases of lower air flow rates (1.5 ach and 3.0 ach) the differences between simulations are even smaller (not shown), reinforcing the use of the WRF simulation forced by the EC-EARTH to study the changes at 1.5 ach and 3.0 ach as well.

4.3.2. Evaporative Cooling

Similarly to the previous subsection, Figure 4.3 shows the monthly average CCP for evaporative cooling with a 6.0 ach flow rate values for period between 1989 and 1999 over the IP, while Figure 4.4 shows the average relative difference between these values.

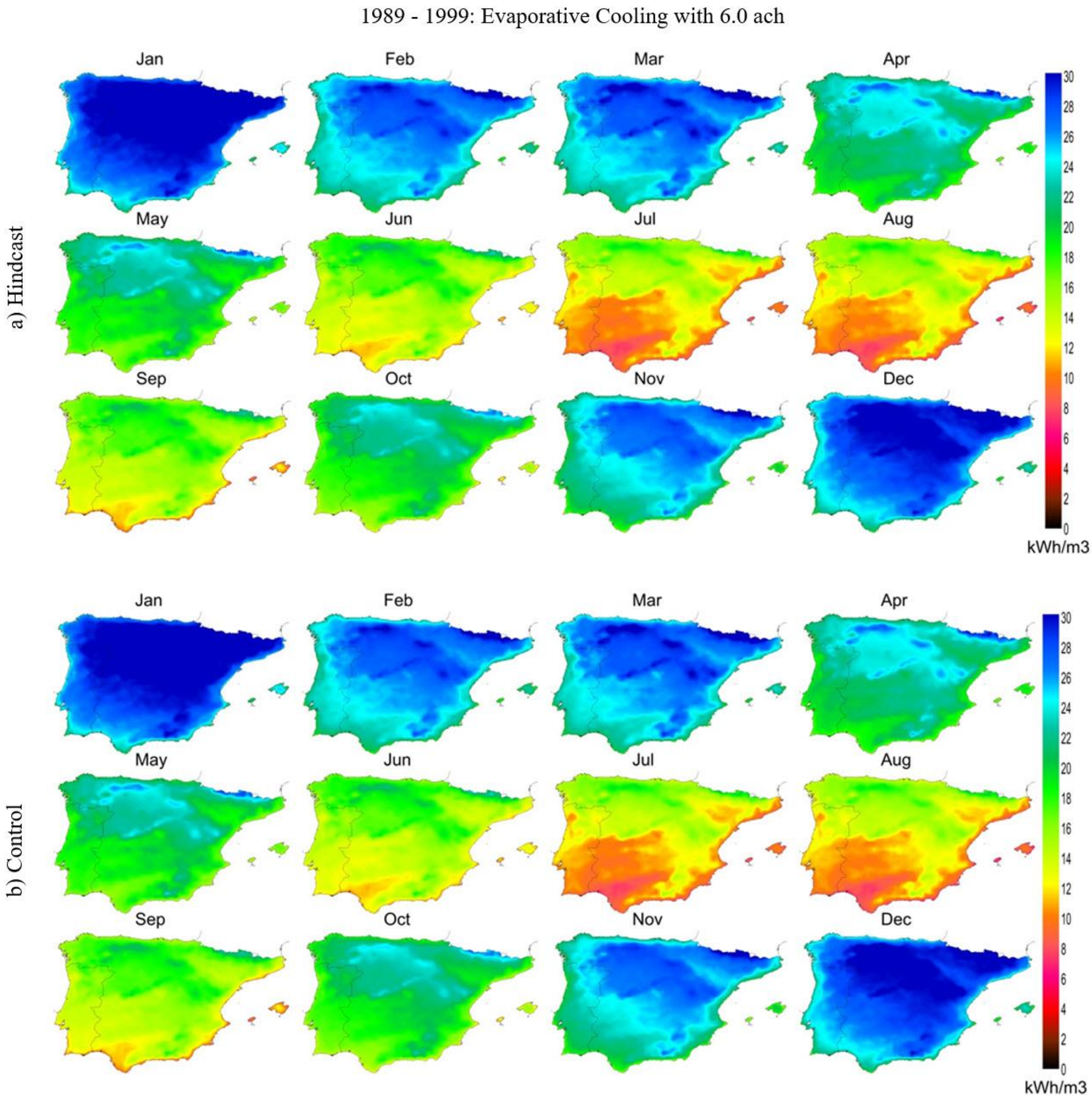

Figure 4.3. CCP Evaporative Cooling, 6.0 ach (1989 to 1999), average monthly values: (a) hindcast; (b) control.

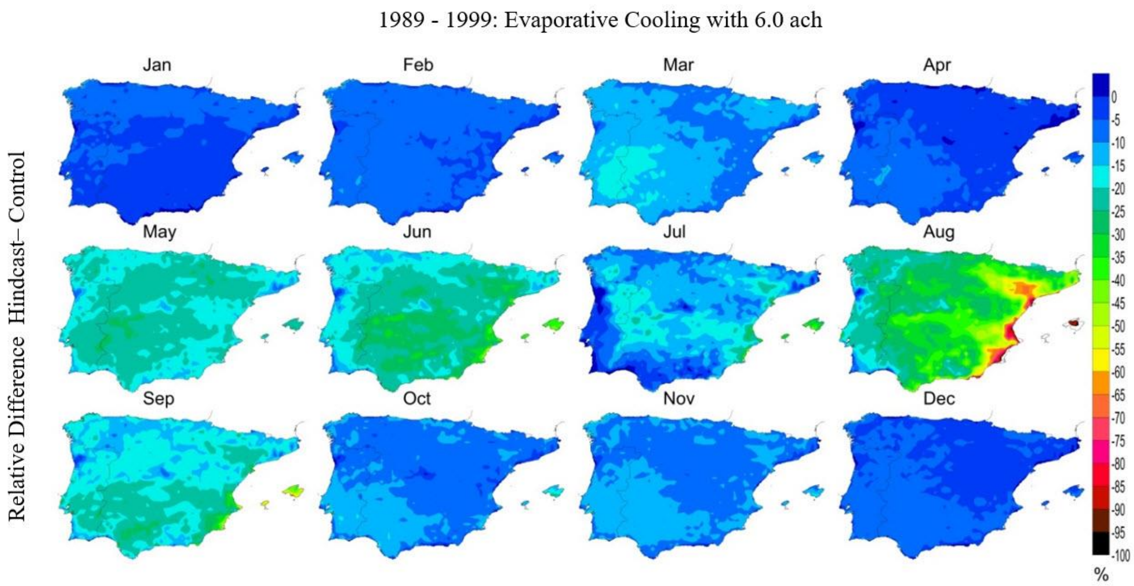

Figure 4.4. CCP Evaporative Cooling, 6.0 ach (1989 to 1999), average monthly values. Relative difference between hincast and control: 100*(hindcast - control)/control.

By comparing figures 4.1 and 4.3, it is clear that the Evaporative Cooling produces higher CCP values than Direct Ventilation. Moreover, over the full annual cycle, CCP values given by hindcast and control simulations are closer to one another for the case of Evaporative Cooling, mainly below 15% deviation for most of the IP. However, for the case of the warmer month of August and at the east coast of the IP, the deviation does reach higher values (generally around 70%). As for Direct Ventilation, these are the cases where CCP tends to have lower values (typically between 4 and 12 kWh/m^3 for hindcast and control, respectively), meaning that lower absolute deviations result in larger relative deviations. Globally, the results for Evaporative Cooling are even better than for Direct Ventilation, meaning that EC-EARTH forced simulations can also be used to assess CCP for Evaporative Cooling for the end century at a large spatiotemporal scale.

4.4.Future Projections

The main goal of the present section is to provide an Iberian dataset for the CCP for both Direct Ventilation and Evaporative Cooling and to assess the climate change impact on the effectiveness of Direct Ventilation and Evaporative Cooling, for different rates of ventilation for the end of the 21st century. For this, we use the WRF simulations forced by EC-EARTH for present climate, 1970-2000 (historical) and for future climate, 2070 to 2100 (future).

Firstly, the future potential of Direct Ventilation is assessed for the 1.5 and 6.0 ach flow rates.

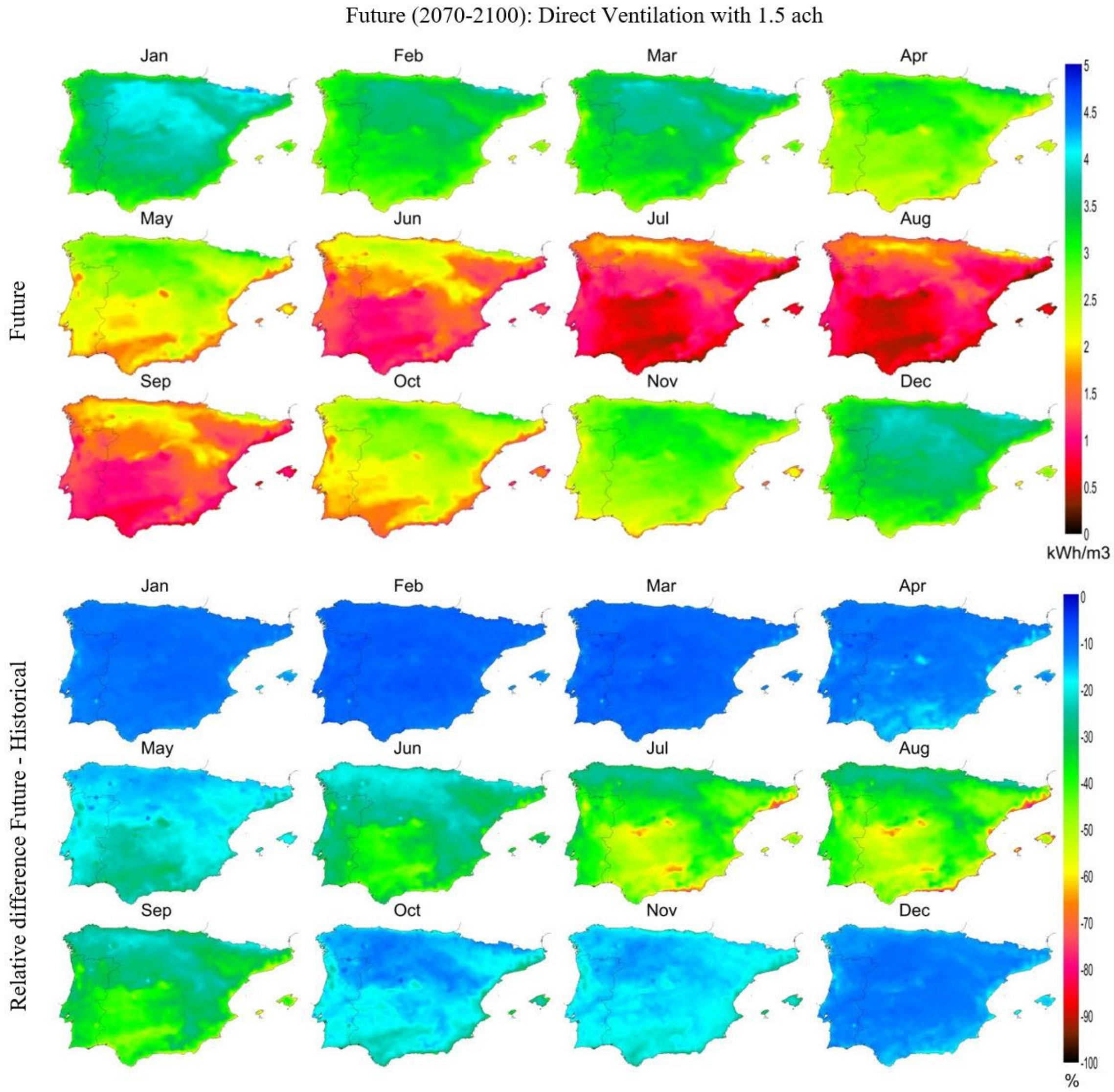

Figure 4.5. CCP Direct Ventilation, 1.5 ach, future climate (2070 to 2100), average monthly values: (top) future values; (bottom) relative difference between future and historical values: 100*(future - historical)/historical

In the case of 1.5 ach (Figure 4.5a), the future CCP generally remains above 2.0 kWh/m^3 from October to March over the entire IP, with the exception of the Guadalquivir basin where it is close to 1.5 kWh/m^3 in October. For the Pyrenees and the Iberian Cordillera CCP remains above 3.0kWh/m^3 for this period. However, during summer, where the CCP is of higher utility, these values tend to shrink, especially for the warmer months of July and August, where CCP is around 1.0 kWh/m^3 for the majority of the IP, and even lower for the Guadalquivir basin and the south central part of Iberia, with values equal to or lower than 0.5 kWh/m^3. The IP´s orography seems to have a significant effect on the CCP, particularly in summer. The low altitude regions, as the Guadalquivir and the Ebro basins present lower CCP values, normally bellow 1kWh/m^3, contrary to the high altitude regions, like the Pyrenees and the Iberian Cordillera where CCP is higher, usually above 2kWh/m^3. During summer, the CCP tends to be lower at the southeast coastal regions of the IP, due to higher temperatures of the Mediterranean Sea.

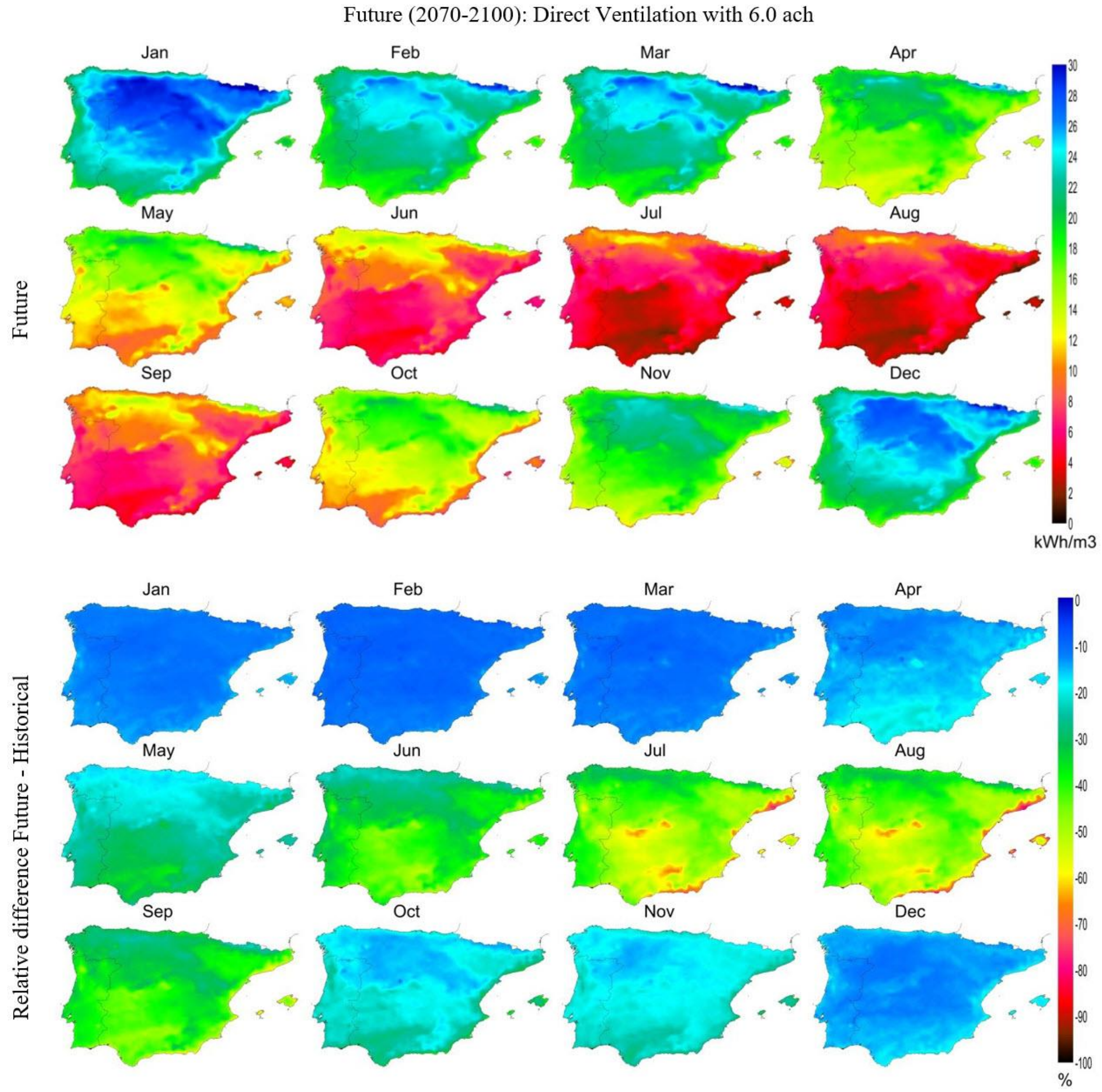

Figure 4.6. CCP Direct Ventilation, 6.0 ach, future climate (2070 to 2100), average monthly values: (top) future values; (bottom) relative difference between future and historical values: 100*(future - historical)/historical.

For the case of 6.0 ach flow rate (Figure 4.6a), even though CCP maintains its spatial and annual heterogeneity over the IP, it is important to note that CCP is generally 6 times higher than for the 1.5 ach, i.e. while the flow rate increases by 4 times, the CCP tends to increase by 6 times. It might be advantageous (depending on the cooling demand) to select a higher flow rate in order to provide more savings.

Regarding the effect of climate change on the CCP offered by the use of Direct Ventilation (Figures 4.5b and 4.6b, for 1.5 ach and 6.0 ach, respectively), it is clear that:

the relative differences in CCP between future and historical simulations increase from the colder to the warmer months: from October to April, the relative differences between historical and future remain below 20% for all the IP and below 10% from January to March with no pronounced spatial heterogeneity for both air flow rates. For the warmer months (May to September), there is a noticeable increase in the relative differences as well a change in the spatial distribution, with the northern part of the IP presenting lower differences in CCP (generally below 30% and 35% for 1.5 ach and 6.0 ach, respectively) and the south and central part reaching 60% for the months of July and August. However, the CCP in these months and locations present lower values due to the higher temperatures, reaching around 0.5kWh/m^3 and 2 kWh/m^3 for 1.5 ach and 6.0 ach, respectively, meaning that small changes will represent higher relative deviations.

Overall, the projections for the CCP of Direct Ventilation show some relevant decreases but these do not seem dramatically affected by the increase in temperatures. The warmer months, when the CCP is of higher interest, still present a considerable amount of potential that can be used to lower the building cooling demand.

For the case of Evaporative Cooling, Figure 4.7a (1.5 ach) shows that CCP is generally above 3.0 kWh/m^3 from October to May. During summer there is a decrease in CCP values due to higher temperatures. However, CCP remains above 2.0 kWh/m^3 all over the summer, with the exception of the east coast line, where CCP lowers below 2.0 kWh/m^3 in the month of August.

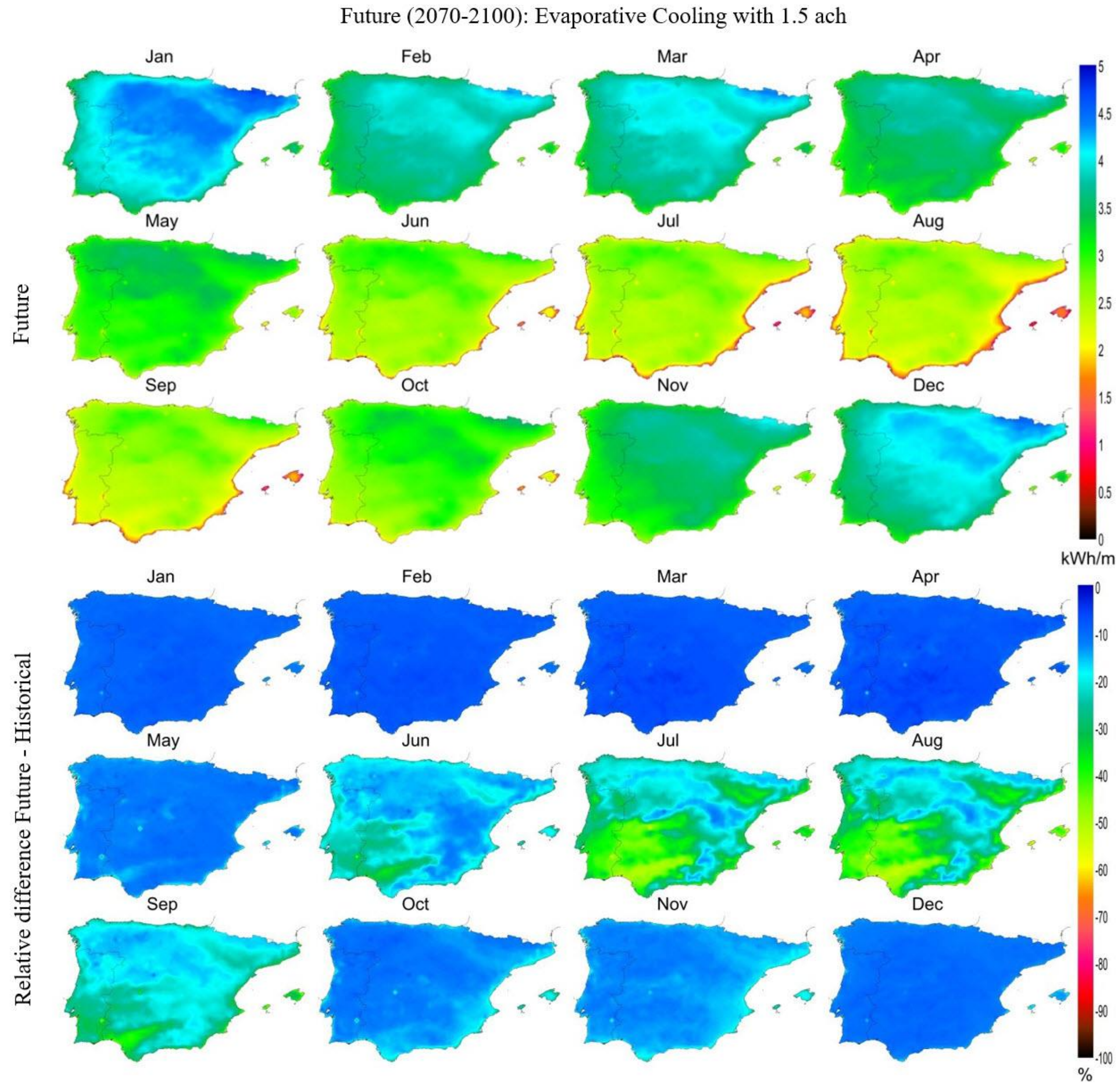

Figure 4.7. CCP Evaporative Cooling, 1.5 ach, future climate (2070 to 2100), average monthly values: (top) future values; (bottom) relative difference between future and historical values: 100*(future - historical)/historical

In the case of the 6.0 ach air flow rate (Figure 4.8a), the CCP spatial heterogeneity is accentuated over the IP, varying from a minimum of 5 kWh/m^3 in the Guadalquivir basin for the month of August, up to a maximum of 30 kWh/m^3 in the Iberian Cordillera and the Pyrenees from December to March. Regarding the effect of climate change on the CCP offered by the use of the Evaporative System (Figures 4.7b and 4.8b, for 1.5 ach and 6.0 ach): i) the relative differences for historical and future simulations conserve the same spatial distribution and heterogeneity for both air flow rates, with higher deviations (around 5%) for the 6.0 ach relatively to the 1.5 ach; ii) the relative differences in CCP between future and historical simulations increase from the cooler to the hotter months: from October to April, the relative differences between historical and future remain below 15% and 20% for all the IP (for 1.5 ach and 6.0 ach respectively) and below 5% from December to April with no pronounced spatial heterogeneity for both air flow rates. From June to September, for both air flow rates, there is a denoted increase in the relative differences as well in their spatial distribution, with minimum values around 30% for the Ebro basin and around 55% for the Guadalquivir basin.

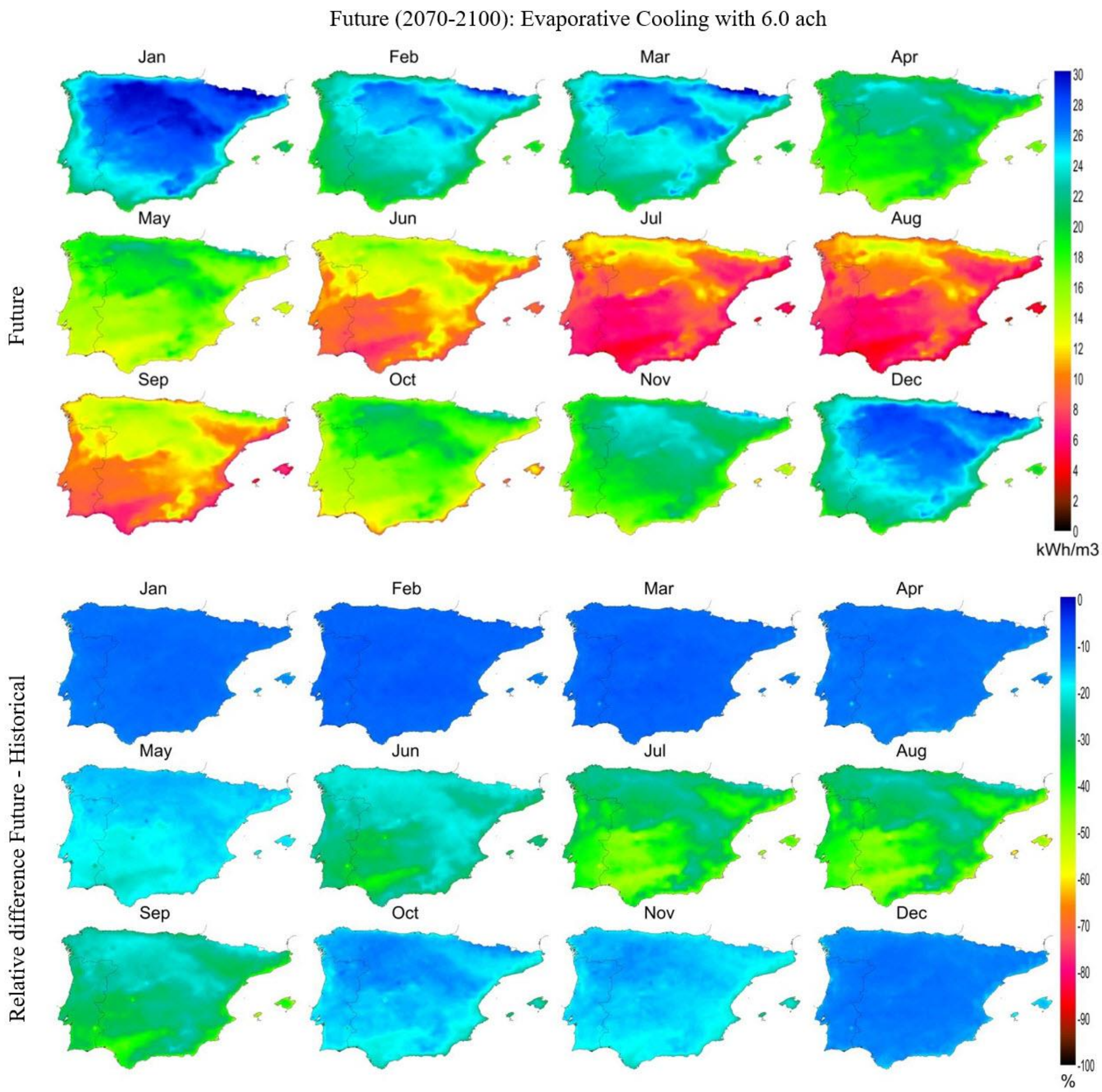

Figure 4.8. CCP Evaporative Cooling, 6.0 ach, future climate (2070 to 2100), average monthly values: (top) future values; (bottom) relative difference between future and historical values: 100*(future - historical)/historical.

Comparing Figures 4.5a and 4.6a with Figures 4.7a and 4.8a, it is clear that: i) the CCP cycle across the IP presents a higher spatial homogeneity for the case of Evaporative Cooling for both air flow rates; ii) predictably, Evaporative Cooling provides higher CCP values over all of the IP along the full annual cycle, however this differences tend to decrease over the coast line due to the presence of higher moist levels in the air since if the air´s relative humidity is elevated at a point where the air is no longer capable of retaining more water, then the temperature of Evaporative Cooling becomes equal to that of Direct Ventilation (Equation 4.3). Nonetheless, for the warmer months (e.g. July and

August), in some regions like the Guadalquivir basin, the CCP of Evaporative Cooling system can surpass the one of Direct Ventilation by a factor of 5, due to low moist levels in the air. However, for other regions, these differences can be dramatically reduced. Normally these are the cases of some coastal regions which have high levels of moisture in the air.

Figure 4.9, provides a comparison between the CCP provided by the Evaporative Cooling and Direct Ventilation systems for the historical and future simulations, for two locations, one inland (Castelo Branco, Portugal: 39º48’39” N; 7º30’28” W) and the other in a coastal area (Mañón, Bares, Spain: 43º44’22” N; 7º42’35” W). It shows a significant difference in using Evaporative Cooling in relation to Direct Ventilation between a coastal and an inland location for both historical and future simulations. Using Evaporative Cooling in a coastal location presents a small improvement in the CCP relatively to Direct Ventilation, with around 10% growth over the full annual cycle, for both present and future climates. For the inland location, these differences are 40% and ~59% over the full annual cycle, reaching a maximum of 111.8% and 183.1% in August. This shows a clear advantage of the Evaporative Cooling systems inland, especially during the warmer months, where CCP is of higher utility.

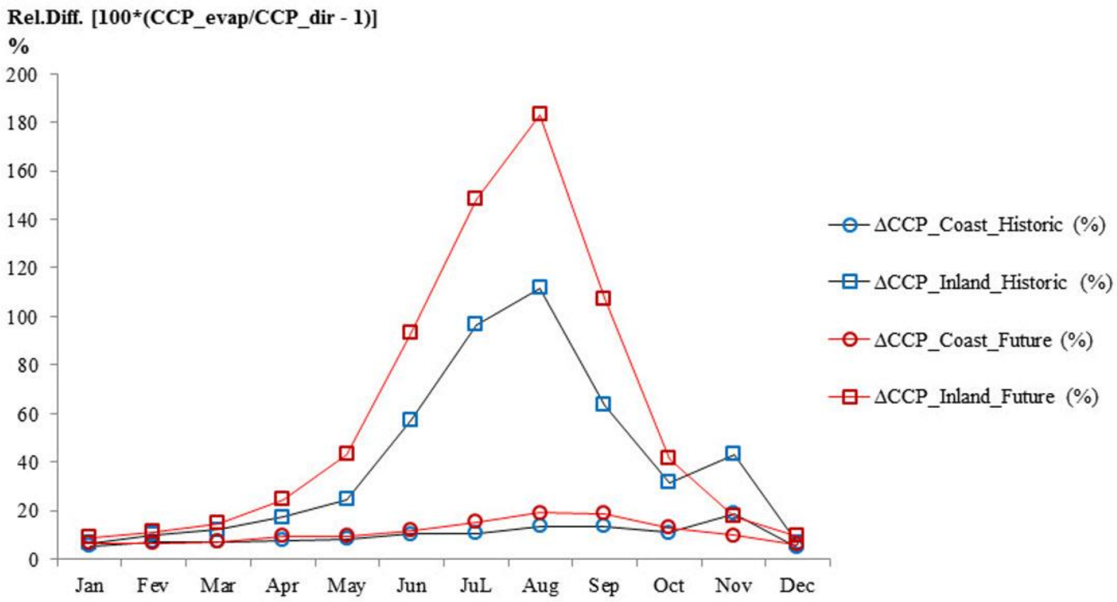

Figure 4.9. Relative difference (%) between CCP for Evaporative Cooling and Direct Ventilation for 1.5ach reference and passive rates of ventilation for a region in the coastline and in the inland of the IP, for historical and future climate

Overall, Evaporative Cooling is less affected by Climate Change than Direct Ventilation, because is not so directly affected by the differences in the dry bulb temperature, meaning that such systems can still be efficient even in the climate change scenario that is expected for the late century

Finally, in addition to the decrease in CCP caused by climate change at the late century for both Direct Ventilation and Evaporative Cooling, due to warmer temperatures, it is also expected that cooling consumption in buildings should increase.

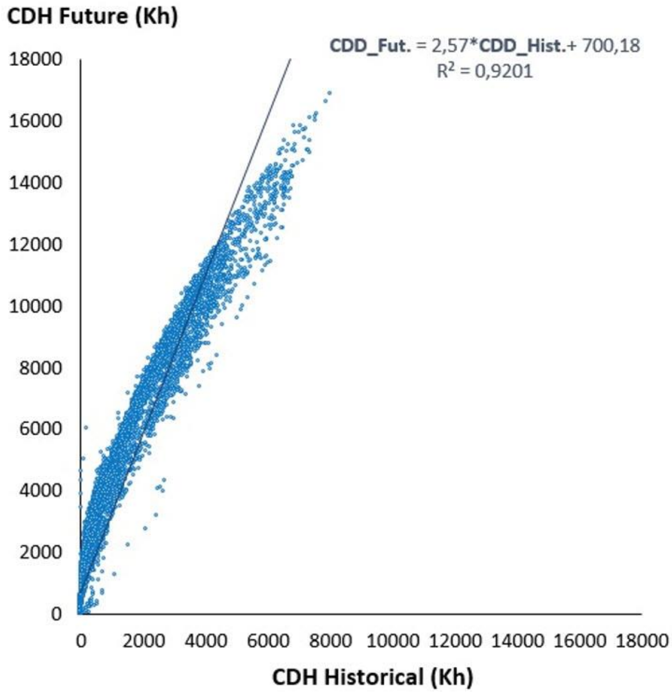

Figure 4.10. Relation between yearly average CDH for future climate data set (vertical axis) and yearly average CDH for historical data set (horizontal axis).

Table 4.1. Relative difference between yearly average CDH for future and historical climates for the main urban centres in the Iberian Peninsula.

City	Longitude (W)	Latitude (N)	100*(CDH_Fut.-CDH_Hist) / CDH_Hist. (%)
Braga	-8.250	41.330	298
Coimbra	-8.420	40.210	214
Faro	-7.970	37.000	165
Lisbon	-9.150	38.700	187
Madrid	-3.678	40.410	285
Malaga	-4.390	36.750	331
Porto	-8.600	41.133	279
Seville	-5.970	37.380	104
Valencia	-0.350	39.450	451

Figure 4.10 displays the relation between CDH for both historical and future climate datasets given by equation 4.3 for all the considered locations in the Iberian Peninsula (21870 grid points). A linear fit to the scatter points reveals a possible linear relation between future and historical CDH, with a correlation factor (R^2) around 0.92 representing an average increment on future CDH (relatively to historical) superior to 2.5 times (for most of locations in the Iberian Peninsula). This means that the expected increase in cooling demand is more pronounced than the decrease in the climatic cooling potential offered by any of the ventilated passive cooling systems considered for the same building type and occupation. Table 4.1 shows the relative difference between future and historical CDH for some of the main cities in Iberia. Figure 4.10 also shows major increases in CDH for the future climate for all of the cities, varying from 100% increase (for Seville) to 451% (Valencia).

4.5. Conclusions

In the present study, we assessed the impact of climate change on the future potential of direct ventilation and evaporative cooling, over the Iberian Peninsula (IP). In a first stage, we computed the climatic potential (CCP) of these passive cooling techniques for the period 1989-1999, of climatic simulations performed using the WRF model. Comparison between hindcast and control simulations shows similar spatial and temporal distributions of the CCP over Iberia, both for Direct Ventilation and Evaporative Cooling, and even for the extreme case of a 6.0 ach flow rate. In a second stage, we used the previously validated control simulation for computing and mapping the CCP for Direct Ventilation and Evaporative Cooling for the end of the century (2070-2100), and characterizing the main expected changes.

The main results of the present study can be summarized has follows:

- CCP maintains its temporal and spatial heterogeneity along the IP for control and future simulations for both of the passive systems and flow rates.
- Similarly to the historical simulations, for the future, Evaporative cooling always provides higher potential for the same annual cycle independently of the location in the Iberian Peninsula.
- Even though the CCP provided via the Evaporative Cooling system is higher than the one provided by Direct Ventilation, for some regions, like coastal regions, this increment is reduced by the high levels of moist in the air. Since these kind of systems usually possess higher investment costs, they might not be advantageous (relatively to Direct Ventilations) at some coastal regions.
- The CCP for both systems is expected to decrease by the end of the century due to increased temperatures; even for the higher flow rate of 6.0 ach, this differences remain globally under 40% (in the worst cases) over the entire annual cycle for both systems.
- The differences between historical and future are less pronounced for Evaporative Cooling system than for Direct Ventilation. This differences are mostly below 10% (in relation to Direct Ventilation) over the IP for the warmer months.
- Lastly, the expected increase in cooling demand is more pronounced than the decrease in the climatic cooling potential offered by any of the ventilated passive cooling systems considered.

In summary, it should be mentioned that even in a global warming context Direct Ventilation and Evaporative Cooling still offer an interesting potential over most of the

IP. By providing an insight on the CCP over a large spatiotemporal, this study offers valuable information for the strategic decisions concerning the passive cooling systems for any location in IP. Moreover, this in turn may serve as an incentive to their implementation. The methodology presented here can further be applied for any RCM results, permitting the assessment of the climate change impact on different passive cooling systems for any other region.

5. Conclusions

The work presented in thesis can be divided in three parts from which we can draw the main conclusions. The first part of this work, presented in chapter 2, focus in the development and test of a simplified method to compute the savings in building cooling demand by use of passive cooling systems based on ventilation. This method is based on the CCP and its main goal is to provide a simple way to directly estimate the cooling demand savings in buildings using several ventilated passive cooling systems. The method is independent of the building characteristics depending only on the climate under consideration, the passive cooling system and its flow rate, as well as the building comfort set point temperature. The method was tested against an extensive numerical simulation set using thermal simulation software TRNSYS. The simulation campaign contemplated the case of an administrative building located in Geneva (Switzerland), with a variety of constructive and operational configurations (solar protection, thermal mass and insulation, internal gains) and an important set of passive cooling techniques (direct ventilation, evaporative cooling, air-soil heat exchangers, thermal phase-shifting, as well as combination thereof) with diverse sizing and flow rates, yielding a total of 7776 configurations/simulations. For the referred configurations, the correlation between the UCP potential and the effective savings was analysed in terms of annual cooling energy savings. It was shown that calculation of the useful cooling potential on an hourly basis underestimates the effective savings by an average of 31%, due to the fact that the building thermal inertia is not taken into account, while calculation of the UCP on a daily basis reproduces the effective savings with less than 1% error in average. For a monthly basis, UCP overestimates the effective savings. In fact, it was shown that, if the data is monthly available, the error remains below 20% for half of 7776 the cases, although it may be quite more important (up to 70% for extreme cases, in particular, for cases where the model indicates close to 100% coverage and the associated cooling demand is low). As a key result, this method can be used for setting up of a climatic potential database in a monthly time step, for assessing the potential of these passive cooling techniques on a large spatiotemporal scale, for which integrated building simulation becomes prohibitive.

In chapter 3, the CCP methodology was applied to a high resolution climatic dataset produced using WRF forced by the ERA-Interim, for the Iberian Peninsula. This resulted in a dataset for the CCP offered by the use of direct ventilation and evaporative cooling with a 9km resolution in the Iberian Peninsula and covering a 19 years period. The results show that the CCP values are temporally and spatially heterogeneous both for direct ventilation and evaporative cooling. Evaporative cooling always provides higher potential for the same time periods and for all of the Iberian Peninsula domain considered. However, in some coastal regions, evaporative cooling provides less than 10% larger climatic cooling potential compared to direct ventilation due to the high moist levels in the air. Furthermore, CCP values show a clear asymmetry between the northern and southern part of the Iberian Peninsula for both direct ventilation and evaporative cooling, with higher values in the northern part due to lower air temperatures.

Finally, in the third part of this work, presented in chapter 4, Two present climate simulations were used to compute the climatic cooling potential: the first one employed the hindcast simulation where WRF is forced by the reanalysis ERA-Interim and the second employed the EC-EARTH forced historical run. The results of these simulations were compared and it was possible to verify that both simulations show a similar spatial and temporal distributions of the CCP over Iberia, both for Direct Ventilation and Evaporative Cooling, even for the extreme case of a 6.0 ach flow rate. Therefore, indicating that EC-EARTH forced simulations can be used to characterize the CCP for Direct Ventilation and Evaporative Cooling for the end century, and to assess the impact of climate change on the CCP in Iberia. In this way, a third simulation using WRF and also forced by the EC-EARTH model results for future climate (following the RCP 8.5) was analysed. The output of the latter simulation was used to map the CCP for direct ventilation and evaporative cooling over Iberia for the late century (2070 to 2100). Additionally, the cooling degree hours for the historical and future climates was also assessed in Iberia. The results show that CCP maintains its temporal and spatial heterogeneity along the IP for both historical and future climates. Due to increased temperatures, CCP values form future climate do suffer a decrease relatively to the historical climate, however, even for the higher flow rate of 6.0 ach, these differences remain globally under 40% (in the worst cases) over the entire annual cycle for both systems. The differences between Historical and Future climates are less pronounced for Evaporative Cooling system than for Direct Ventilation. Lastly, the expected increase in cooling demand accessed by the cooling degree hours is more pronounced than the decrease in the climatic cooling potential offered by any of the ventilated passive cooling systems considered.

Succinctly, the work present in this thesis provides an innovative and simple methodology to estimate the cooling demand savings in buildings using any ventilated passive cooling system, regardless of building physical/thermal properties, without the need to use thermal simulation software. From this methodology, it was possible to map the climatic cooling potential, and to correlate it with cooling demand savings, over a large spatiotemporal scale for both present and future climates in the Iberian Peninsula. The present work can/should be extended for different regions, such as Europe and U.S.. Furthermore, as future work, ideally it should be completed with an economic analysis on the ventilated passive cooling systems, boosting the implementation of such systems and therefore contributing to the mitigation of the use of fossil fuels and the associated greenhouse gases emissions directly in the largest energy consuming sector.

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