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

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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 the 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 Circulation Model
RCM	Regional Climate Model
RCP	Representative Concentration Pathway scenarios
UCP	Useful cooling potential (kWh per m^3 of ventilated building)
WRF	Weather Research and Forecasting model

Symbols

c	Heat capacity of air (kWh/K.kg)
ρ	Air density (kg/m^3)
v	Ventilation flow rate (air changes per hour)
vref	Standard ventilation flow rate (kg/h or air changes per hour)
vvnt	Passive cooling system´s ventilation flow rate (kg/h or air changes per hour)
Tbld	Building temperature (ºC)
Tvnt	Passive cooling system output temperature (ºC)
Tset	Building´s set point temperature (ºC)
Text	Outdoor temperature (ºC)
UCP	Useful cooling potential (kWh/m^3 of ventilated building)
Qcool	Building´s cooling load (kWh)
η	Evaporative cooling system´s efficiency
Twb	Wet bulb temperature (ºC)

1. Introduction

1.1. Climate Change and Energy in Buildings

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 [1]. Climate change and the need to reduce greenhouse gas emissions 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 [2]. 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.

The sector of Buildings is the main energy consuming sector, representing 40% of the energy consumption in Europe, surpassing industry (31%) and transportation (26%) [3;4]. 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 [5-8] 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 [9], 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 [10]. The main scope of this study are direct ventilation and evaporative cooling systems.

1.2. Direct Ventilation and Evaporative Cooling

Direct ventilation can be used when the outside temperature is lower than the building´s temperature and there is cooling demand. 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 [11]. Direct ventilation is frequently used during night and therefore designated as night cooling. Direct ventilation systems efficiency depends on the difference between indoor and outdoor temperatures and the air flow rate, however it is limited to the building´s thermal mass and the cooling demand [12]. Direct ventilation systems can provide substantial reduction of the cooling demand [13-15].

Evaporative cooling systems, direct or indirect, use the principle of water evaporation for heat absorbing. Direct evaporative cooling systems inject air directly into the building, while in the indirect evaporative cooling systems the outside air does not flow into the building, but exchanges heat with the inside air through a heat exchanger. To avoid condensation, in the case of direct evaporative cooling systems, the inlet air can pass through a membrane which retains some of the water vapor [16;17]. In the last decades, evaporative cooling has seen its use increased, mostly in air conditioning, owing to its simplicity in structure and use of natural energy in the form of latent heat of water [18;19]. Evaporative cooling is used extensively for cooling in climates with medium to low humidity [20] and has proven its economic and technical feasibility through several studies [21-24]. A study on indirect evaporative cooling suggests that these systems may represent a fifth of the global building air-conditioned market over the next 20 years [17].

The implementation of passive cooling systems usually requires 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 was performed, namely, [11] for direct night ventilation and [21] for evaporative cooling.

1.3. Cooling demand savings – state of the art

The relation between climate variables, like temperature and humidity, and the cooling potential offered by the use of a given passive cooling system has been only addressed in a few studies, however, most of them did not aim at providing an estimation method of the cooling demand savings linked to the passive cooling potential. Artman et al. [11] 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 is a index that provides the amount of the climatic availability for direct cooling ventilation, however no relation between the cooling potential and cooling demand savings is established. Recently, in Campaniço et al. [25], this index was further developed and generalized to incorporate humidity, in a way that it can also be used to describe the climatic evaporative cooling [25;26]. 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 [26]. The concept 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). This study has shown that the calculation of the UCP performs better when is based in daily values, with an average error inferior to 1%. Nonetheless, even in the case where UCP is computed at a monthly basis, the effective savings are only overestimated by an average of 11%.

Based on the aforementioned results, Campaniço et al. [25] established a monthly CCP database for both direct ventilation and evaporative cooling for the present climate in the Iberian Peninsula (IP). Their results reveal that within Iberia, the CCP has a spatial and temporal asymmetric distribution for Direct Ventilation as well for as for Evaporative Cooling. From May to September (cooling season), the CCP is generally above 1kWh per m^3 of building for direct ventilation and 3kWh per m^3 of building for evaporative cooling. Evaporative cooling provides consistently higher values than direct ventilation, but the difference between the two systems is below 10% in the coastal regions. For the case of a typical office room in the region of Lisbon, for the warmer month (August), direct ventilation and evaporative cooling can provide 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 [27] simulated the future performance of low-energy evaporative cooling systems using UKCP09 climate projections and pointed out a higher potential for the application of evaporative cooling for the UK. Also for the UK, Gupta and Gregg [28] 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 houses by 2080. Frank [29] 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, nonetheless this study does not include the impact on possible passive cooling techniques. Recent studies [30-32] 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. [33] where the climate change effect is considered in the dimensioning of Phase Change Materials to be used to reduce cooling loads. Nevertheless, 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.

1.4. Future climate – climatic cooling potential

In order to access the effect of the climate change in the passive cooling systems, the present study uses the results of a state-of-the art Regional climate model (RCMs). RCMs have the ability to represent physically regional and local atmospheric processes, they have become an increasingly sophisticated tool for the development of high-resolution climatologies, for present and future climates [34-38]. Here, a set of regional climate simulations performed with the WRF model is used, including two present climate runs (hindcast and historical) and one future scenario simulation. The synchronized present climate simulation (hindcast), of this set of simulations, was previously used to characterize the climatic cooling potential of direct ventilation and evaporative cooling for Iberia [25]. In the current paper the hindcast run is used to validate the historical CCP results. The present climate historical simulation results is then compared with the future results allowing to project the changes in the context of global warming.

Thus, the main goal of this study is to assess the climate change impact on the climatic cooling potential and the energy savings, for direct ventilation and evaporative cooling, in the Iberian Peninsula. To accomplish this objective a detailed comparison between the present and future climate cooling properties is investigated, and a thorough analysis of the expected changes is performed. This analysis permits a first and unique insight on the sustainability of direct ventilation and evaporative cooling at a large spatiotemporal scale for the future climate in Iberia. The main research questions addressed are: 1) how good is the historical run to characterize the present climate CCP for direct ventilation and evaporative cooling in Iberia; 2) how will the CCP change due to global warming in this region; and, 3) what will be the expected signal in building energy savings?

In section 2 the methods are described. Section 3 provides a comparison between EC-EARTH (historical) and ERA-Interim (hindcast) for the same time period. In section 4, the two EC-EARTH forced model simulations, historical (1971-2000) and Future (2071-2100) are used to assess the climate change effect on the CCP. Finally, in section 6, the main conclusions are drawn.

2. Methodology and data

2.1. Methods

The methods used here follow closely Campaniço et al. [25]. In this study, the CCP is defined to allow the estimation of the cooling demand savings using different passive cooling systems in buildings at any spatiotemporal scale. The 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:

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

$$v = \begin{cases} v_{vnt} & if \;\; T_{vnt} < T_{bld} \\ v_{ref} & if \;\; T_{vnt} \geq T_{bld} \end{cases} \qquad \text{(Eq.1)}$$

In equation 1, *CCP* refers to the Climatic Cooling Potential in kW per m^3 building (or kWh per m^3 building when integrated over time), 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 exchanges per hour,

T_{vnt} is the ventilation temperature (°C), T_{bld} is the temperature inside the building (°C) and T_{ext} is the air outside temperature (°C).

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

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

At certain days, e.g. often in winter and in cool nights during the other seasons, the CCP might be higher than the actual cooling load of the building, however its contribution can only be as high as the cooling load. Therefore, the CCP must be compared with the cooling load 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_{vnt} in equation 1 is simply given by the dry bulb ambient air temperature, ($T_{vnt} = T_{ext}$). Evaporative cooling is computed considering an efficiency η of 50% (relatively to the wet bulb temperature, T_{wb}):

$$T_{vnt} = T_{ext} + \eta(T_{wb} - T_{ext}) \qquad \text{(Eq.2)}$$

The CCP will be assessed accordingly to equation (1). Here, the set point temperature, T_{set} is 26°C, the reference flow rate v_{ref} is 1.5 ach (1.5 m^3/h per m^3 building), between 7h to 19h (occupation) and equals zero between 19h to 7h. This represents the case of an administrative building. The passive cooling systems will be evaluated for two flow rates: 1.5 ach (activated whenever T_{vnt} is inferior to T_{set}) and 6.0 ach (reduced to reference if T_{vnt} is above T_{set}).

The comparison of the CCP for present and future climates enables the characterization of the impact of global warming for each of the passive cooling systems considered. The climate dataset results are described in the next sub-section.

2.2. Iberia

In the present study, we use a set of high resolution, regional climate simulations for Iberia using the Weather Research and Forecasting model (WRF) [39], 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 1) with 144x111 and 162x135 grid points, respectively. A comprehensive description of the model set-up and parameterizations used can be seen in

Soares et al. [40] and Cardoso et al. [41]. The Iberian climate is characterized by large inter-annual and spatial variability. This variability is substantially enhanced by complex topography and coastal processes [40;42;43]. While the northwestern highlands are one off the wettest regions in Europe, (mean annual precipitation above 2800 mm), in the south-eastern coast values below 200 mm are the driest [41]. Furthermore, especially in the latter region, Iberia is occasionally affected by flash floods. High Mediterranean Sea surface temperatures and topographic enhancement of convective systems are often responsible for high intensity precipitation events, which sometimes lead to flash floods. While the northern and west coasts have mild temperatures almost all year round, the central areas of the peninsula have a large inter-annual variability, with cold winters and hot summers.

2.3. Climate Data: WRF high resolution simulations

In this work three simulations were performed: one hindcast simulation for the period 1989-1999, and two climate simulations, a historical run for 1970-2000 (historical) and a future run for 2070-2100 (future). The hindcast simulation uses ERA-Interim reanalysis [44] as boundary conditions. In the latter, numerical weather forecasts are combined with observations (station data, satellite data, radar, buoy etc…) using data assimilation techniques. The observational assimilation provides a dynamically consistent climate state which embodies a realistic 3D representation of the current climate. The WRF hindcast simulation is a dynamical downscaling of ERA-Interim, which is thus synchronized with current climate. This enables its evaluation through a direct comparison with observations [40, 41, 46, 47]. The hindcast results were used and assessed in diverse studies, from precipitation properties, spatial and temporal distributions of Portuguese temperature [40; 41], moisture recycling processes [42], coastal surface wind and low-level jets [46], Iberian solar resources [47], clouds [43], offshore and onshore wind resources [48] and wildfire propagation models [49;50]. The historical and future simulations are dynamical downscallings of the EC-EARTH global climate model [45]. Global climate models (GCMs) provide a 3D representation of the Earth’s past climate, which is statistically comparable with historical climate, however it is not synchronised. Additionally, GCMs can also simulate future climate. The WRF, EC-EARTH downscaling results have also been used in several studies related to precipitation [51], temperature [52], wind [48,53] and solar radiation [54]. In this study, the hindcast simulation is used to supply a CCP benchmark and enable the assessment of the historical simulation. The latter provides a past climate reference for the evaluation of the climate change signal, since this has to be performed only with simulations with similar boundary conditions (i.e. forced by GCM). To aid the comprehension of the climatic simulations used in the present study, a flowchart is presented in figure 2.

2.4. Cooling Degree Days

For the sake of simplicity, in the present article we will use the concept of Cooling Degree Hours (CDH) to provide a rough assessment how cooling demand will change with global warming over Iberia. To do so, we will use the same climate dataset previously introduced, and compute the average of the sum of the differences between hourly outside temperatures and set point temperature (whenever positive), for each year of the historical and future climate datasets according to equation 3:

$$CDH = \frac{\sum_{y=1}^{31}\sum_{i=1}^{n}(T_{ext}-T_{set})^{+}}{31} \qquad \text{(Eq.3)}$$

In equation 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 (*Text* > *Tset*).

Note that other factors (such as insulation, building inertia, internal and solar gains, etc.) may affect cooling needs [55,56]. In the current analysis, these factors will not be taken into account. This is in particular the case for solar gains, since solar radiation does not significantly change from historical to future climate [54]. The difference between the hourly building set point and outside temperature is the greatest impact factor in cooling demand (for a same building with the same use).

3. Evaluation of the historical present climate

The purpose of this section is to evaluate the CCP for direct ventilation (subsection 3.1) and evaporative cooling (subsection 3.2) given by the historical simulation for the present climate. In this way, we compare the CCP computed via the climatic data output given by the hindcast simulation, forced by the ERA-Interim reanalysis (hindcast) with the one forced by the EC-EARTH model historical run [45]. Since the hindcast comprises 11 years only, the overlapping period is selected from the historical run to perform a fair comparison. Ideally, both simulations should display similar CCP values and spatial distributions for supporting the use of WRF results to assess the climate change impact on the CCP.

3.1. Direct ventilation

The CCP varies nonlinearly with air flow rate (equation 1), therefore, to assess the differences in CCP computed via hindcast and historical runs, one should take different flow rates into account. The temperatures time series given by each simulation (hindcast and historical) are obviously different. Since the CCP is affected by the product between temperatures and flow rate (equation 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 3 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 historical simulations, respectively. Figure 3 shows a similar spatial and temporal evolution between the CCP values. To better assess the differences between CCPs, Figure 4 shows the average relative differences for the CCP over the IP, for the period between 1989 and 1999.

For the cooler months (Jan to Apr and Sep to Dec), where the CCP has larger values (typically over 15 kWh/m^3) due to the cooler temperatures, the differences between hindcast and historical simulations remain mostly below 20%, and with large areas close to 10%, meaning that the historical simulations tend to moderately overestimate the CCP in relation to the hindcast simulations. For the warmer months (May to Aug), the relative differences increase, especially over the east coast of the IP. However, these are the cases where the CCP has lower values, therefore a low absolute difference (typically 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 the CCP from historical 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.

3.2. Evaporative Cooling

Similarly, to the previous subsection, Figure 5 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 6 shows the average relative difference between these values.

By comparing figures 3 and 5, it is clear that the Evaporative Cooling produces higher CCP values than Direct Ventilation. Moreover, over the full annual cycle, the CCP values given by hindcast and historical 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 the CCP tends to have lower values (typically between 4 and 12 kWh/m^3 for hindcast and historical, 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 the CCP for Evaporative Cooling for the end century at a large spatiotemporal scale.

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. In the case of 1.5 ach (Figure 7a), 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 the CCP remains above 3.0 kWh/m^3 for this period. Nonetheless, for the summer period, where the CCP utility is increased, these values tend to shrink, especially for the warmer months of July and August, where the 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 noteworthy importance on the CCP, particularly in summer, where the low altitude regions (e.g. Ebro basin) present lower CCP values (<1kWh/m^3) relatively to high altitude regions (e.g. Pyrenees > 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.

For the case of 6.0 ach flow rate (Figure 8a), even though the CCP maintains its spatial and annual heterogeneity over the IP, it is important to note that it is generally 6 times higher than for the 1.5 ach flow rate, 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 7b and 8b, 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, without 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 9a (1.5 ach) shows that the 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, the CCP remains above 2.0 kWh/m^3 all over the summer, with the exception of the east coast line, where the CCP lowers below 2.0 kWh/m^3 in the month of August.

In the case of the 6.0 ach air flow rate (Figure 10a), 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 9b and 10b, 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.

Comparing Figures 7a and 8a with Figures 9a and 10a, 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, which is no longer capable of absorbing more water, so that the temperature of Evaporative Cooling becomes equal to that of Direct Ventilation (Equation 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 11, 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: 43°44’22” N; 7º42’35” W). Figure 11 shows significant relative differences between Evaporative Cooling and Direct Ventilation in the inland locations and similar values in the coastal locations for both historical and future simulations. The use of Evaporative Cooling in coastal locations does not provide significant improvements on the CCP values 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 the CCP is of higher utility.

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 12 displays the relation between CDH for both historical and future climate datasets given by equation 3 for all the considered locations in the Iberian Peninsula (21780 grid points). An exponential fit to the scatter points reveals a possible relation between future and historical CDH, with a correlation factor (R^2) around 0.98 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 1 shows the relative difference between future and historical CDH for some of the main cities in Iberia. Figure 12 also shows major increases in CDH for the future climate for all of the cities, varying from 100% increase (for Seville) to 451% (Valencia).

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 historical 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 historical 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:

- The CCP maintains its temporal and spatial heterogeneity along the IP for historical 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) for such 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, for both systems these differences remain globally under 40% (in the worst cases) over the entire annual cycle.
- The differences between historical and future are less pronounced for Evaporative Cooling system than for Direct Ventilation. Except for summer months these anomalies are mostly below 15%. For the summer months the future anomalies can reach values around 30%.
- 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 could further be applied for any RCM results for any other region, allowing the assessment of the climate change impact on different passive cooling systems, such as buried pipes and the phase shifting [25]. These systems have proven its viability and capability of reducing the cooling demands in buildings, this is documented among several studies [9][13-15][21-24][57-64], The implementation of these systems is also expected to increase among the next decades [17], as so, this work can be used to enhance this implementation and to contribute to wiser decisions even in the context of a changing climate. More practical approaches, considering case studies, and side by side comparison between the models here presented and in situ measurements complemented with economic analysis should be taken into consideration for future studies to supplement and fulfill the present work.

Acknowledgments

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Table 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)	(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

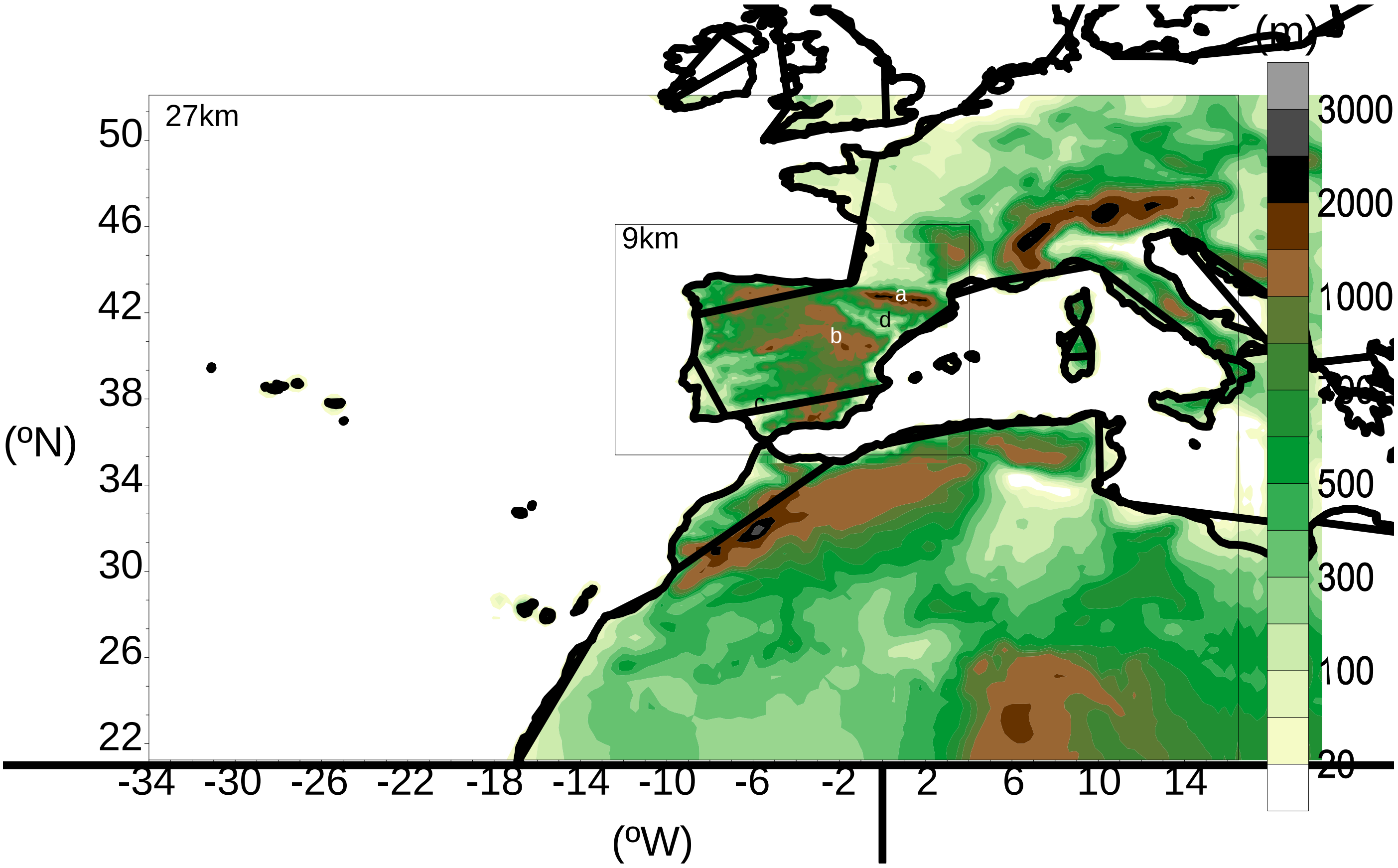

Fig. 1. WRF model domains, at dx=27km (full map), and dx=9km (black rectangle); a) Pyrenees, b) Iberian Cordillera, c) Guadalquivir basin, d) Ebro Basin

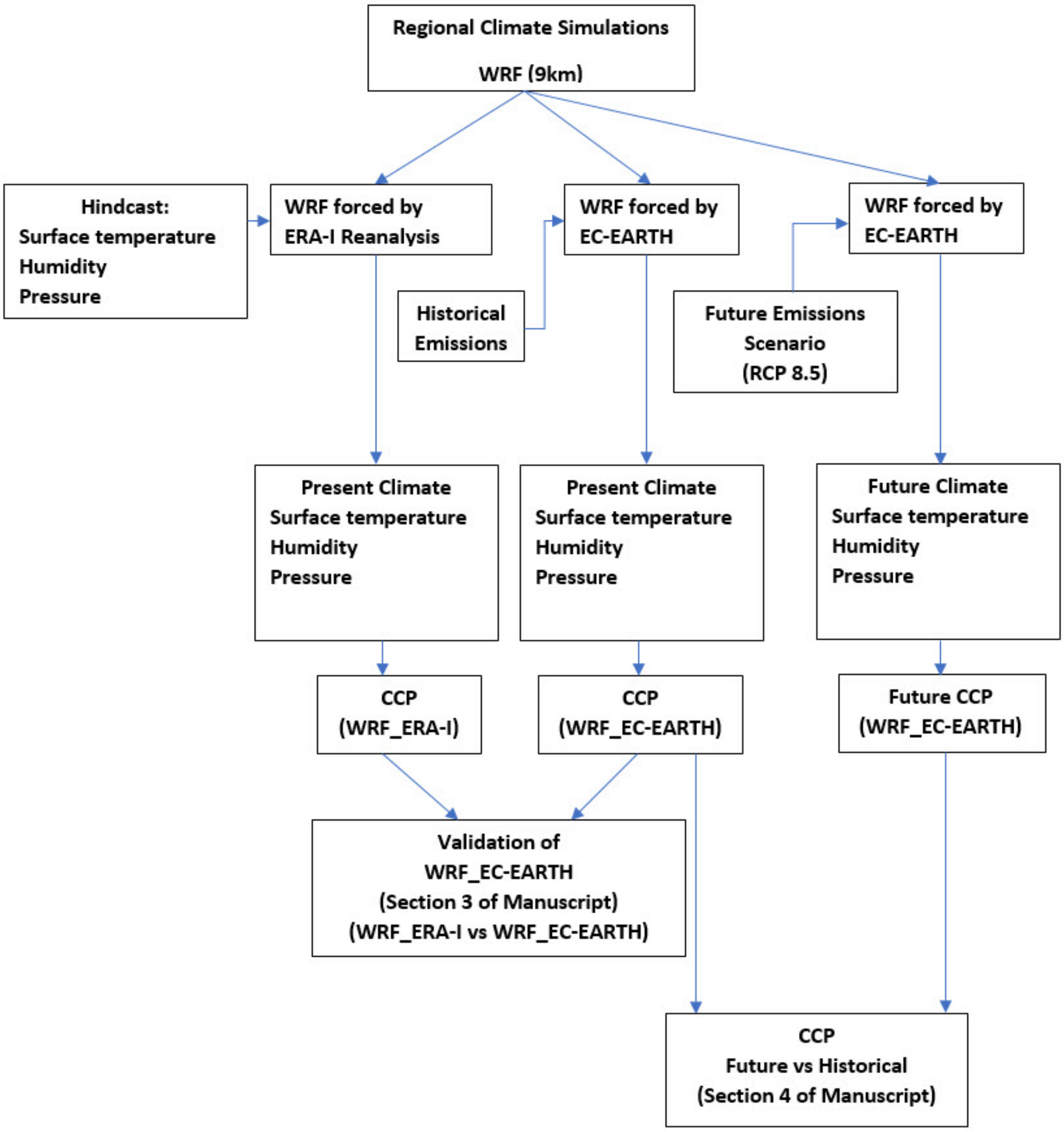

Fig. 2. Flowchart – Climate Simulations.

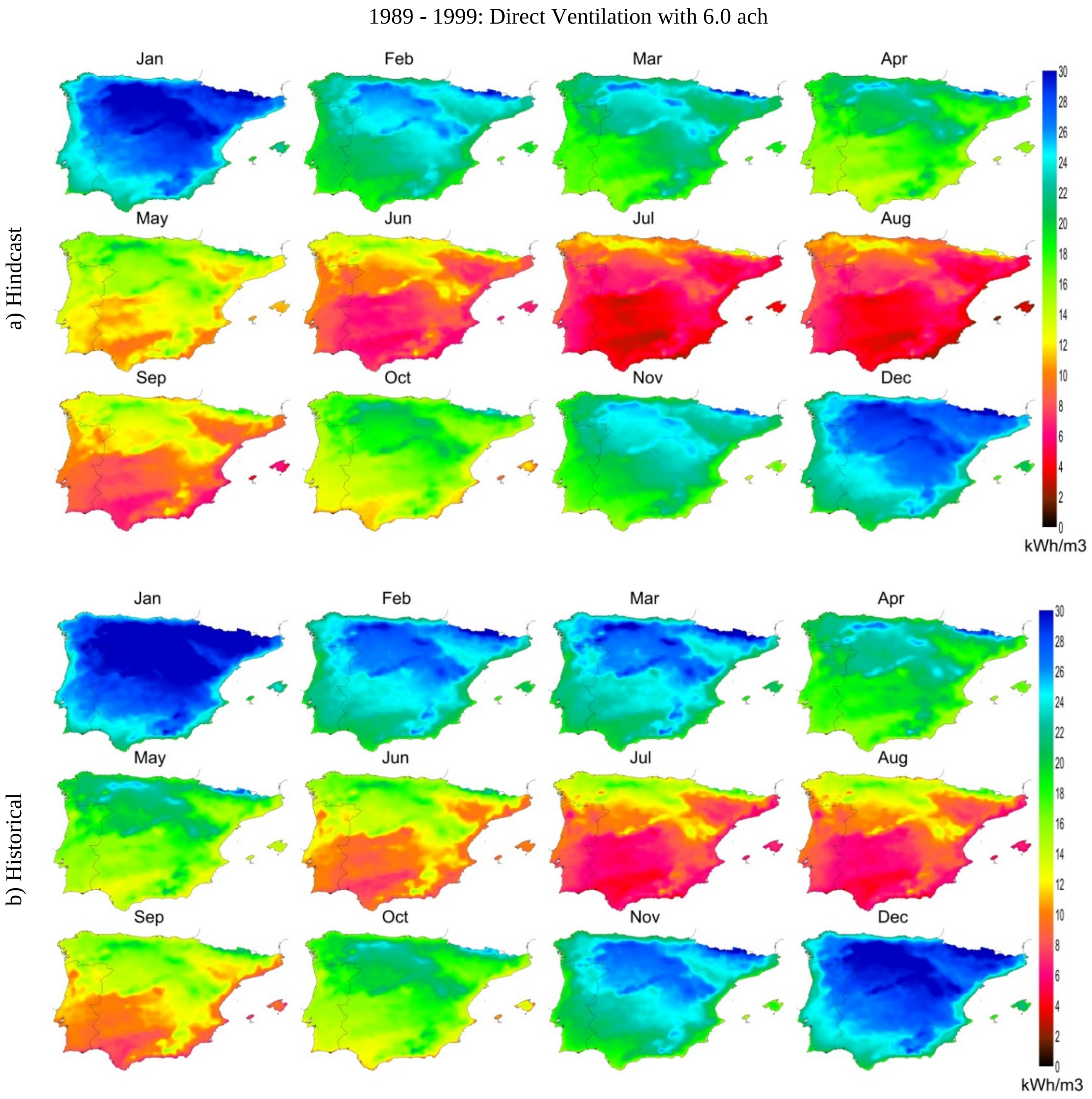

Fig. 3. CCP Direct Ventilation, 6.0 ach (1989 to 1999), average monthly values: (a) hindcast; (b) historical.

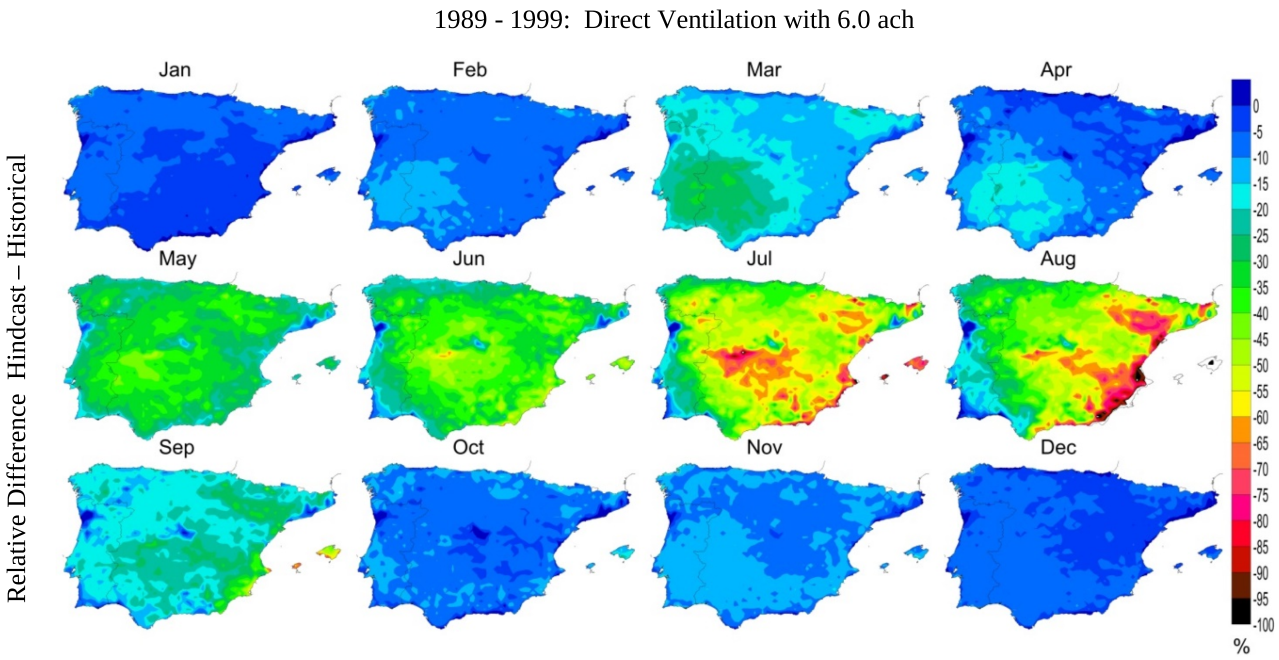

Fig. 4. CCP Direct Ventilation, 6.0 ach (1989 to 1999), average monthly values. Relative difference between hincast and historical: (hindcast - historical)/ historical.

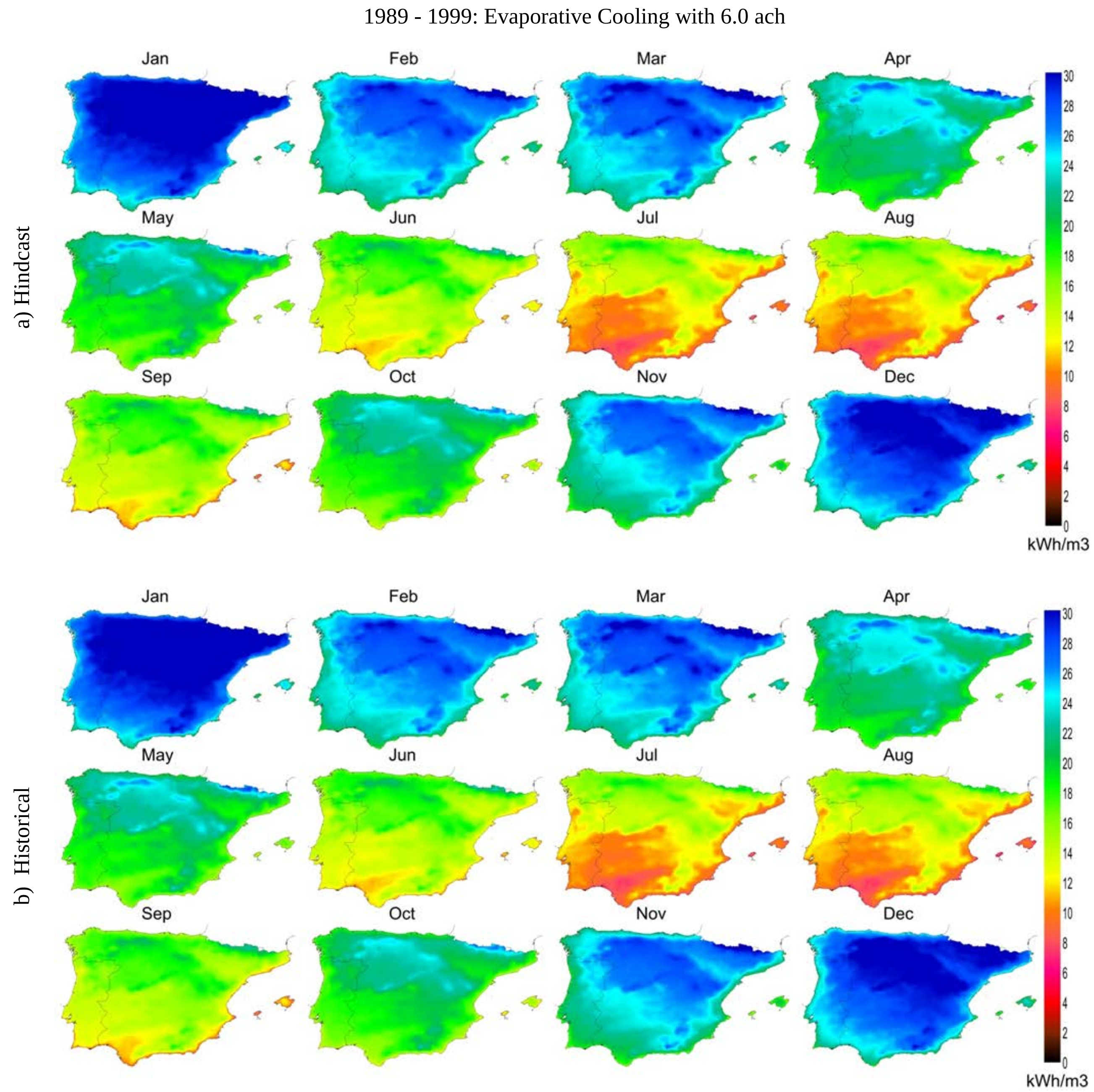

Fig. 5. CCP Evaporative Cooling, 6.0 ach (1989 to 1999), average monthly values: (a) hindcast; (b) historical.

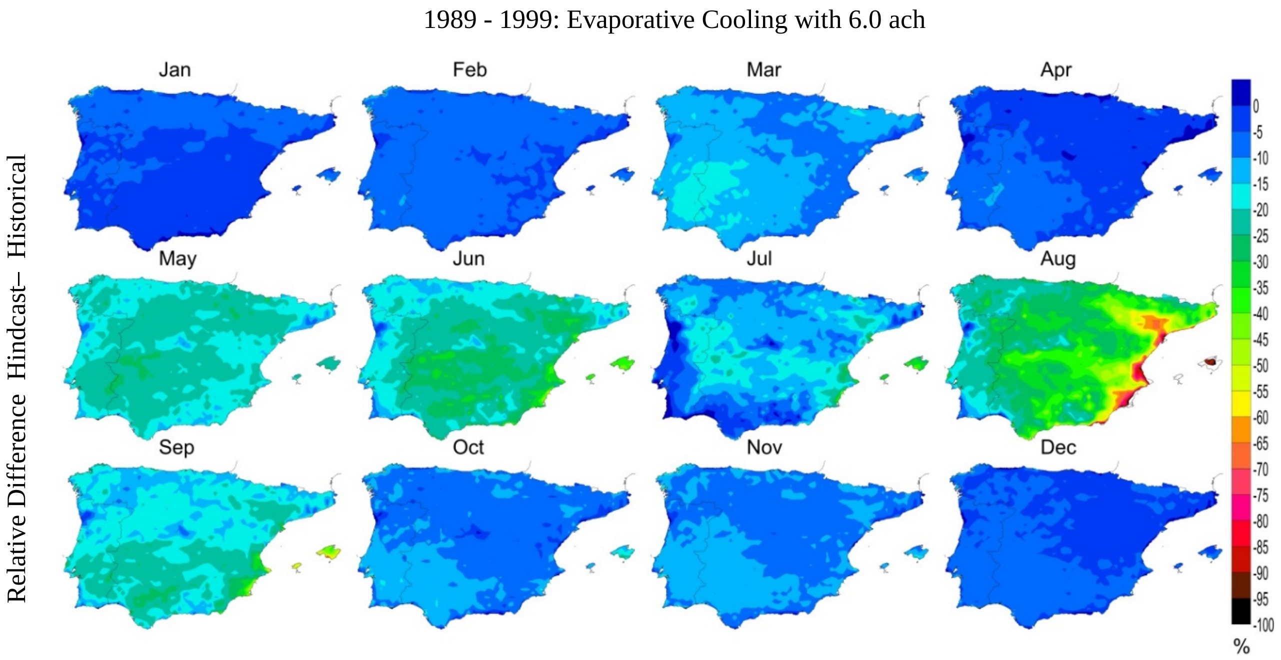

Fig. 6. CCP Evaporative Cooling, 6.0 ach (1989 to 1999), average monthly values. Relative difference between hincast and historical: (hindcast - historical)/ historical.

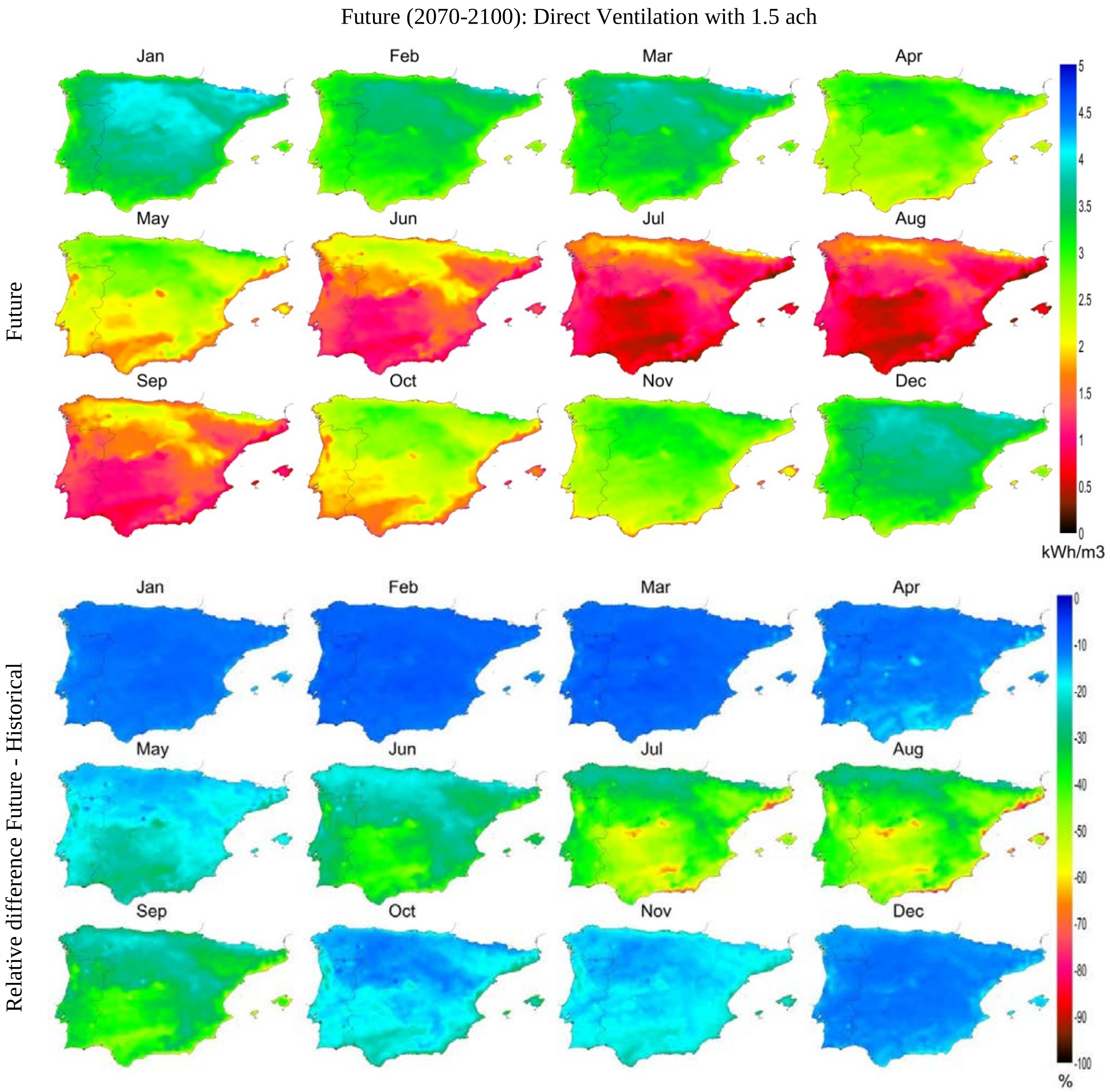

Fig. 7. CCP Direct Ventilation, 1.5 ach, future climate (2070 to 2100), average monthly values: (a) future values; (b) relative difference between future and historical values: (future - historical)/historical.

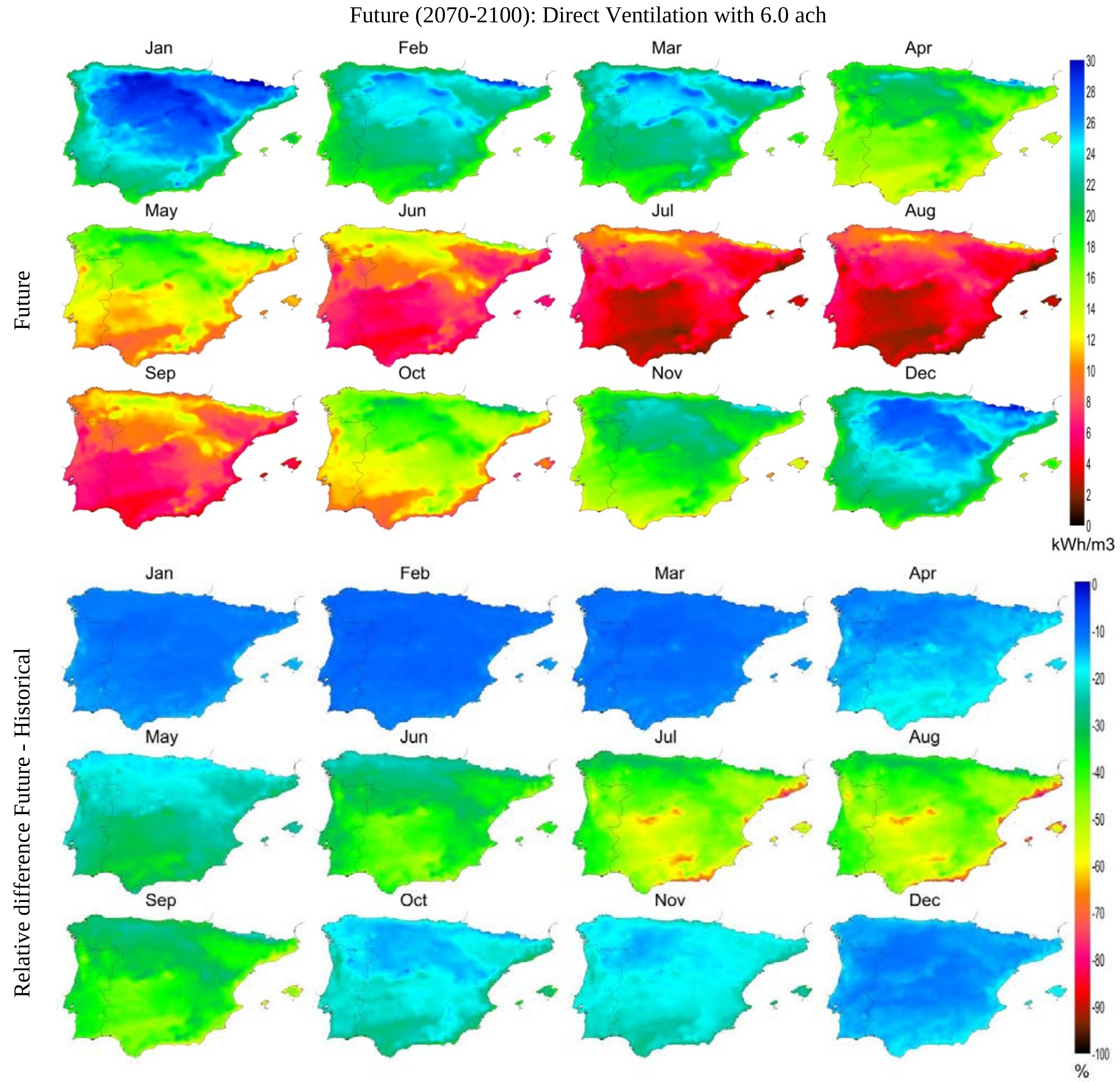

Fig. 8. CCP Direct Ventilation, 6.0 ach, future climate (2070 to 2100), average monthly values: (a) future values; (b) relative difference between future and historical values: (future - historical)/historical.

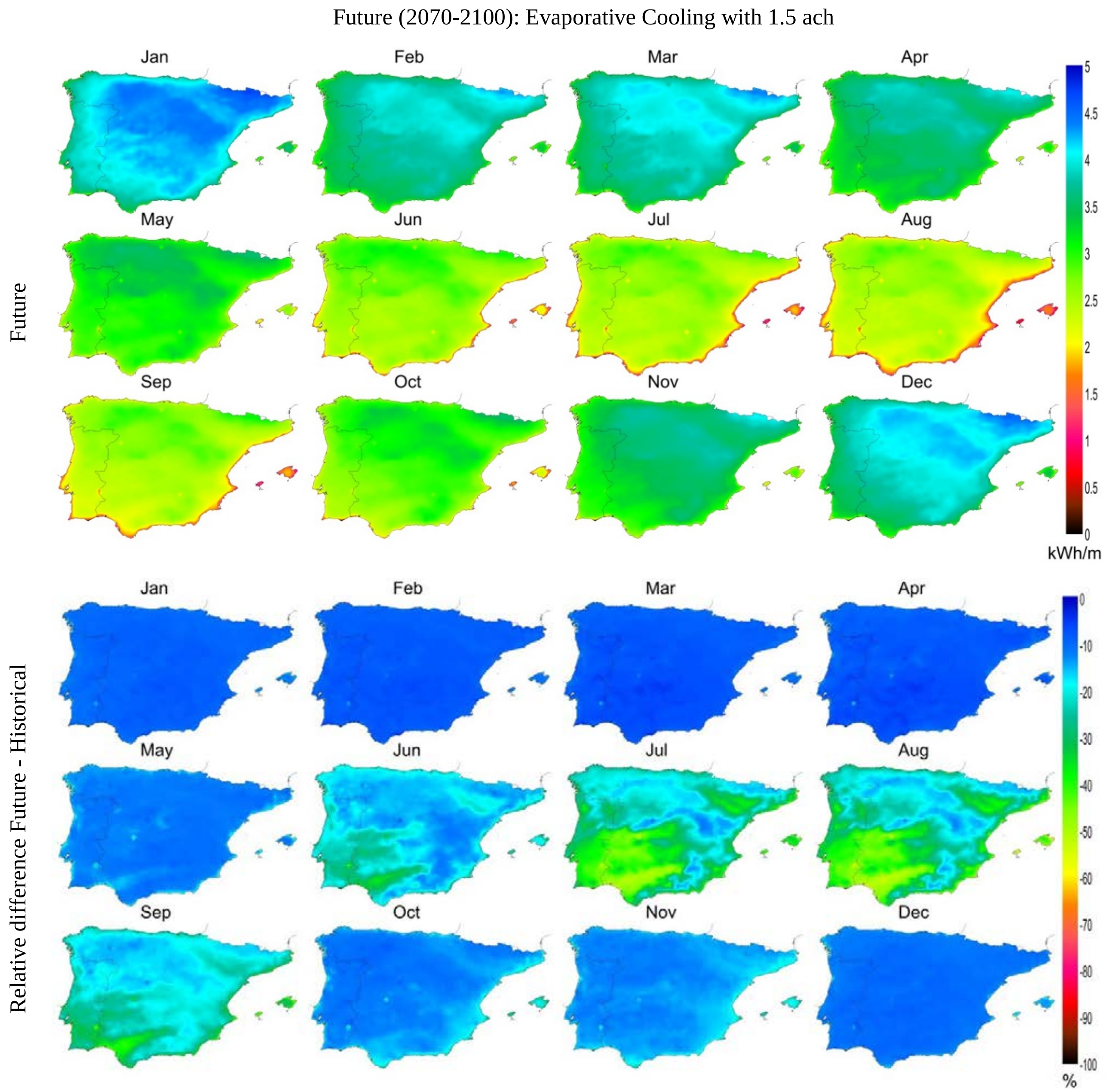

Fig. 9. CCP Evaporative Cooling, 1.5 ach, future climate (2070 to 2100), average monthly values: (a) future values; (b) relative difference between future and historical values: (future - historical)/historical.

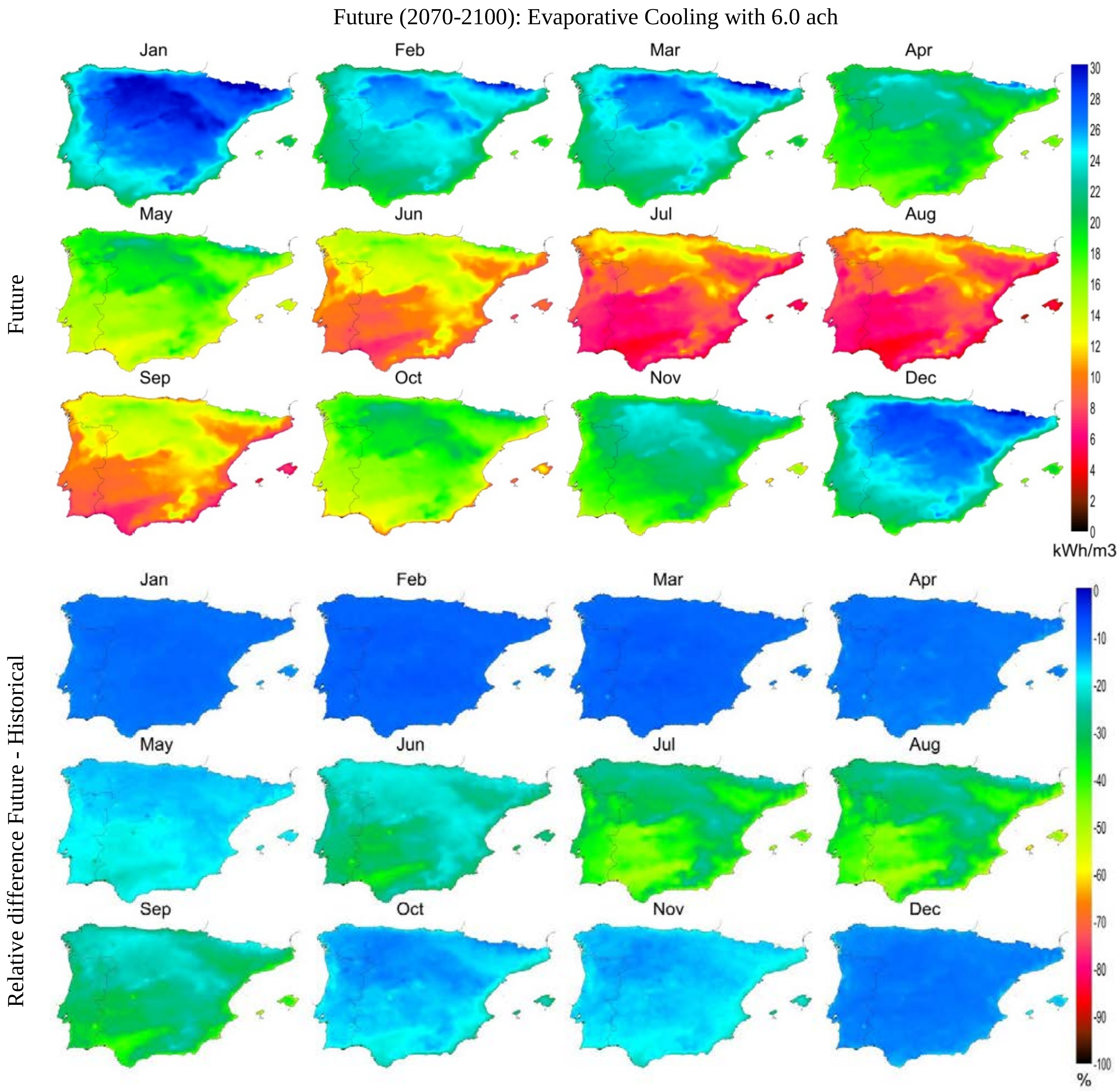
Future (2070-2100): Evaporative Cooling with 6.0 ach

Fig. 10. CCP Evaporative Cooling, 6.0 ach, future climate (2070 to 2100), average monthly values: (a) future values; (b) relative difference between future and historical values: (future - historical)/historical.

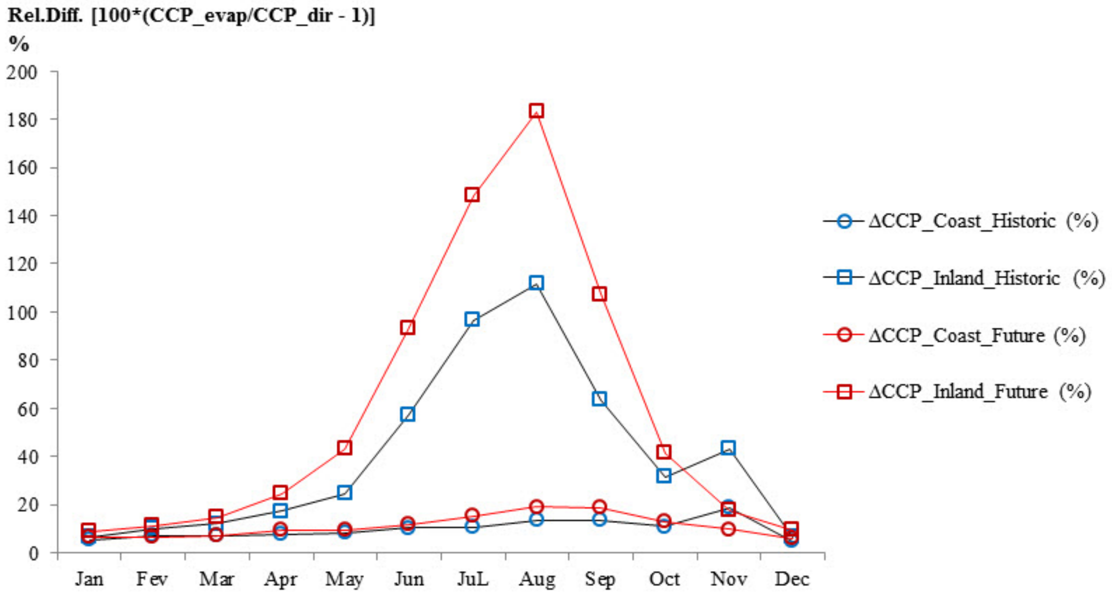

Fig.11. Relative CCP difference between Evaporative Cooling and Direct Ventilation for 1.5ach flow rate, for a region in the coastline and in the inland of the IP, for historical and future climate.

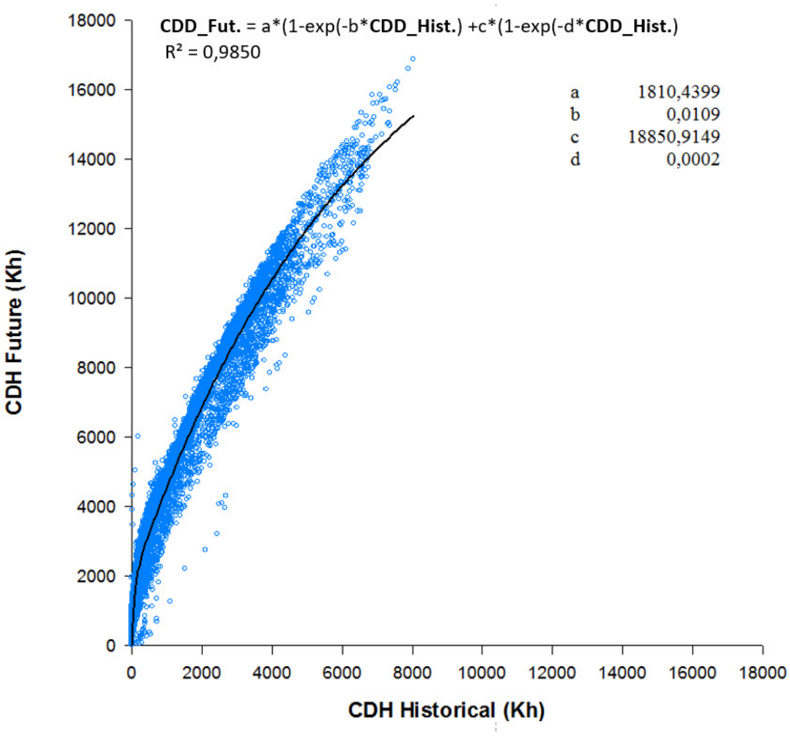

Fig.12. Relation between yearly average CDH for future climate data set (vertical axis) and yearly average CDH for historical data set (horizontal axis).