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Estimating building cooling energy demand through the Cooling Degree Hours in a changing climate: A modeling study

Ferdinando Salata [a,*], Serena Falasca [b,c], Virgilio Ciancio [a], Gabriele Curci [b,c], Stefano Grignaffini [a], Pieter de Wilde [d]

[a] Department of Astronautical, Electrical and Energy Engineering - Area Fisica Tecnica, University of Rome "Sapienza", Via Eudossiana 18, 00184 Rome, Italy
[b] Center of Excellence in Telesensing of Environment and Model Prediction of Severe events (CETEMPS), Department of Physical and Chemical Sciences, University of L'Aquila, 67100 L'Aquila, Italy
[c] Department of Physical and Chemical Sciences (DSFC), University of L'Aquila, 67100 L'Aquila, Italy
[d] Chair of Building Performance Analysis, University of Plymouth, United Kingdom

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ABSTRACT

The increasingly hot and long summers due to the climate change will cause a significant increase in energy demand for cooling systems, especially in highly-densely populated regions. The cooling energy needs of buildings are proportional to the Cooling Degree Hours, which consist in the cumulative sum of the positive differences between the hourly outdoor temperature and the indoor comfort temperature. In this work, this quantity is computed using gridded temperatures predicted by the Weather Research and Forecasting model for the years 2000, 2019, 2050 and 2080 across Italy. This allows investigating the evolution of the cooling energy needs on a national scale, following the climate-change related trend of the ambient temperature. For climate projections, an intermediate (RCP4.5) and a high emissions (RCP8.5) scenario defined by the Intergovernmental Panel for Climate Change have been considered. Findings show that results of 2050-RCP8.5 and 2080-RCP4.5 are very close, both in terms of amount of operational hours and cooling degree hours. The maximum level of cooling degree hours has increased more in the recent past than it will grow in the future, even according to RCP8.5. Yet in 2080 about 70% of Italy will reach levels of cooling degree hours not touched in 2000.

1. Introduction

Energy-efficient retrofit of the building stock is a significant challenge which requires careful planning and prioritization in order to meet government policy targets (Wiechers, Persson, Grundahl, Connolly & Bernd, 2018). Globally, the building sector is responsible for about 32% of global annual energy use (United Nations Statistics Division, 2018), but detailed examination is arduous since it is a fragmented and heterogeneous industry. Furthermore, the context is constantly evolving as the use of individual buildings (residential, hospitality, commercial, etc.) changes over time and technologies and systems progress. The climatic forcing which affects the entire built environment is a further variable that is added to these specific aspects (V. Ciancio et al., 2020). Overall, the energy consumption of buildings in individual countries (Salata et al., 2020) is closely linked to the general climate trend and to the local meteorological conditions (Cao, Dai & Liu, 2016), regardless of the energetic quality of the single building (Pérez-Andreu, Aparicio-Fernández, Martínez-Ibernón & Vivancos, 2018).

It is now widely accepted that human activities and the related anthropogenic emissions have caused a global warming compared to the pre-industrial era. The future climatic forcing is usually estimated by means of numerical climate models assuming the future evolution of greenhouse gas emissions (Yang, Yan & Lam, 2014), through specific scenarios (or pathways) (Falasca, Curci & Salata, 2020).

The general rise in the average temperature of the planet is leading to significant changes in the energy consumption of the whole built environment (Larsen, Petrović, Radoszynski, McKenna & Balyk, 2020; Milojevic-Dupont & Creutzig, 2021). Winters in cold climatic zones are becoming less and less severe (Ciancio et al., 2021), with consequent benefits on the heating demand of buildings (Pagliaro et al., 2015). On the other hand, summers in temperate areas (characterized by mild climates) are becoming longer and hotter (Wang, Wang, Kaloush &

* Corresponding author.
E-mail addresses: ferdinando.salata@uniroma1.it (F. Salata), serena.falasca1@univaq.it (S. Falasca), virgilio.ciancio@uniroma1.it (V. Ciancio), gabriele.curci@aquila.infn.it (G. Curci), stefano.grignaffini@uniroma1.it (S. Grignaffini), pieter.dewilde@plymouth.ac.uk (P. de Wilde).

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Shacat, 2021), with a consequent increase in cooling demand (Tian, Beck, Pan & De Wilde, 2019) to maintain buildings thermally comfortable (Peruzzi, Salata, De Lieto Vollaro & De Lieto Vollaro, 2014). Most of the world population lives in these geographical areas, where usually refrigeration is a more energy-consuming process than heating (Gi, Sano, Hayashi & Toshimasa Tomoda, 2018; Salata et al., 2020). All this could lead to a high demand for energy in the next decades (Imhoff et al., 2004). Predicting the evolution of energy needs deriving from summer air conditioning on a national scale is extremely hard (Bardhan, Debnath, Gama & Vijay, 2020; V. Ciancio et al., 2020). Indeed, the elements that should be considered in the energy analysis of the buildings are many and change over time with the lifetime of the building (Tanasa, Dan, Becchio, Corgnati & Stoian, 2020). However, a first indication of heating or cooling need of building can come from the study of the difference between indoor air temperature and external air temperature (Bardhan et al., 2020). Since such temperature difference is the driving force for any heat transfer, it gives an indication of energy demand for space conditioning, independently of construction features (geometric ratios, orientation, etc.) and systems characteristics (coefficient of performance, transmission loss, etc.) (de Wilde, Tian & Augenbroe, 2011). Seasonal variations and shifts between heating and cooling dominated periods (Dolinar, Vidrih, Kajfež-Bogataj & Medved, 2010) can be accounted for by using different baseline temperatures (de Wilde & Coley, 2012). However, a common baseline value used to assess cooling demand is 26 °C (UNI. UNI/TS 11300–1, 2014), as stated in the legislation (Nicol & Humphreys, 2002).

1.1. Background

Several studies have explored future energy needs of the built environment for different countries across the world. The study by Olonscheck et al. et al. (Olonscheck, Holsten & Kropp, 2011) on Germany is based on the analysis of macro-statistical data at national level and on future projections. A similar method was applied by Eyre and Baruah (Eyre & Baruah, 2015) in the analysis of uncertainties about future energy demand in the United Kingdom. The study by Roshan et al. (Roshan, Orosa & Nasrabadi, 2012) provides a local analysis of some specific Iranian sites. Similar work is performed by Morakinyo et al. (Morakinyo et al., 2019), who focused on the Hong Kong metropolitan area. The importance of mapping large areas together with data on energy needs is well illustrated in the work by Moller et al. (Wiechers et al., 2018) which proposed the creation of a European online atlas. Zheng and Weng (Zheng & Weng, 2019) created a map of the area surrounding Los Angeles (USA) using precise and geo-referenced data collected thanks to microclimatic control units and analyzing future scenarios up to 2050. Larsen et al. (Larsen et al., 2020) realized maps of Europe to investigate the evolution of degree days, based on historical data spanning 1996 - 2005 and making projections up to 2050. With a similar approach, van Schijndel and Schellen (van Schijndel & Schellen, 2018) determined the future deviations of energy needs of museums creating maps on a European scale.

Rouault et al. (Rouault, Ossio, González-Levín & Meza, 2019) analyzed the variations in the energy performance of the typical building stock in Chile under future climate changes. These works provide valid, but localized and specific indications (Gandini, Quesada, Prieto & Garmendia, 2021). Such single-building approach is suitable when analyzing the needs of historic buildings (Salata et al., 2015), as in the work of Muñoz González, et al. (Muñoz González et al., 2020) on churches in the southern Spain. Perez-Andreu et al. (Pérez-Andreu et al., 2018) analyzed the impact of the climate forecast model on the future energy consumption of their case study. Similarly, Berger et al. (Berger et al., 2014) studied the influence of the climate model on the predictions of the energy simulations of four buildings in Vienna (Austria). Similar work was done by Rey-Hernández et al. (Rey-Hernández et al., 2018) and Andrić et al. (Andrić et al., 2017) on a single building in Valladolid (Spain) and in five European and US cities. Ciancio et al. (V. Ciancio et al., 2019, 2020, 2019) analyzed the evolution of the energy consumption in different European cities in the context of a changing climate.

On an overview level, Cao et al. (Cao et al., 2016) highlighted the generic need of an analysis of the evolution of building energy demand over time, extrapolating data for the last two decades in order to outline realistic scenarios for the future.

Dru Crawley and Linda Lawrie performed a work aimed at developing the global typical weather years (Lawrie et al., 2019). In the UK, the Chartered Institution of Building Services Engineers (CIBSE) provided future climate data as TRY weather files (representing a 'typical' weather year) and DSY weather files used for overheating analysis (UNI. UNI/TS 11300–1 2021). Also in the UK, Eames et al. (Eames, Kershaw & Coley, 2011) contributed to the creation of realistic hourly climate data to predict future scenarios, as the MetOffice did (Weather & climate change - Met-Office 2021).

Many previous studies used cooling degree-day as proxy variable for modeling or estimating the "variation in the day-to-day energy demand" (Kozarcanin, Hanna, Staffell, Gross & Andresen, 2020) In addition to the outdoor temperatures, many other parameters influence energy consumption for cooling and heating, such as the thermal properties of buildings, technology renovation, user behavior (Larsen et al., 2020). This last aspect can be taken into account through an indicator based on hourly rather than daily (even maximum and minimum) temperatures which results then more realistic, such as the Cooling Degree Hours (CDHs). Recent applications of the CDHs concern US (Feng, Duan, Chen, Yakkali & Wang, 2021), China (Shi, Han, Xu & Xiao, 2021), Europe (Castaño-Rosa et al., 2021), Thailand (Assawamartbunlue, 2013) and Sydney (Livada, Pyrgou, Haddad, Sadeghi & Santamouris, 2021).

1.2. Purpose and novelty of the work

Addressing the building stock requires prioritization, as renovation and refurbishment is a slow process (Pan & Pan, 2020). To prioritize improving the efficiency of existing buildings and modernizing energy supply networks, one way can be to look at individual buildings and systems, addressing the vulnerable and inefficient ones first. However, on a national scale, it is also worth looking at the local effects of climate change to identify the most affected areas where the energy needs to make buildings comfortable are greatest. The main goal of this article is the investigation of the evolution of the cooling energy need across Italy in the light of climate change (Huang & Hwang, 2016).

In more detail, the purpose of this study is to fully understand the connections between climate change (past and future) and energy consumption for cooling buildings (Guarda et al., 2020; Mauree et al., 2018). Italy is employed as case study as it is at the center of the Mediterranean area, which results to be a hot spot for the global warming (Ascione, De Masi, de Rossi, Ruggiero & Vanoli, 2016). The use of higher-resolution spatially distributed assessment methods allows to statistically analyzing both the entire territory and local critical areas, which is a first step towards prioritization of interventions. This then can be overlaid with further data on building functions and sensitivity to overheating and building condition survey information. As described in the Background section, extensive recent literature is focused on the investigation of future energy demand of buildings, also in Europe. However, most of previous studies are highly system and building specific and/or based on a daily consumption index (i.e. cooling degree-day). The originality of this study consists first of all in a new kind of application of the Cooling Degree Hours CDHs, linked to the hourly outdoor air temperature. This quantity is proportional to energy consumption. In more detail, it represents exactly the term included in the computation of the energy consumption of a building, as established by the legislation. Mapping CDHs on an entire nation (in this case, Italy) allows to investigate the evolution of national and local energy consumption through a weather variable with high temporal (Jiang, Liu, Czarnecki & Zhang, 2019) and spatial resolutions and regardless of the characteristics of the building stock. The use of a numerical weather prediction model, such as the Weather Research and Forecasting (WRF) model, is a plus due to the high temporal resolution and its extreme adaptability. Indeed, some previous studies on Europe (Berger & Worlitschek, 2019; Larsen et al., 2020; Spinoni et al., 2018) based on CORDEX ensemble database (Giorgi & Gutowski, 2015) are characterized by a maximum temporal resolution of 3 h and a maximum spatial resolution of 0.11° (about 12.5 km). Furthermore, thanks to WRF Cooling Degree Hours are computed taking into account geographical properties (e.g., orography, land use) (Kikumoto, Ooka, Arima & Yamanaka, 2015), also for long time periods and at high resolution (Marana et al., 2019). Furthermore, this methodology can be extended to any other territory, after appropriate fine-tuning.

Such a study may be advantageous to the scientific community and to public and private sector subjects employed in planning energy optimization interventions in buildings. Furthermore, these outcomes may be valuable in the planning of large-scale energy production for the future as well. The information provided here can direct economic efforts and incentives, following criteria of urgency and / or of greater usefulness.

The work and the findings are exposed according to the following scheme: i) description of the investigation method and tools; ii) presentation of the results through space-time graphs and statistical analysis, both on the entire geographical area investigated and on individual cities located at different latitudes; iii) discussion of the results and their generalization; iv) conclusions including a synthesis of the results and contextualization of the work in the scientific panorama.

2. Methodology

Italy is a peninsular country that extends from the European continent towards the center of the Mediterranean Sea, thus presenting a variety of geographical and climatic characteristics (Pinna, 1970). This makes it a representative case study in terms of the evolution of energy demand for cooling buildings in the framework of the climate change (Li et al., 2012). Indeed, its geographical position allows investigating the effects of the climate change in climatic conditions close to those of the central Europe as well as those of southern Europe. Furthermore, Italy is densely populated (except for the mountainous areas) and presents an old building stock with large variation in energy optimization interventions.

In this work, CDHs are used as proxy variable (Montgomery, Gragnolati, Burke & Paredes, 2000) to quantify the cooling energy needs in Italy. This quantity will be described in further detail in Section 2.4. The analysis of CDHs will be carried out for: i) the entire Italian territory, through a mapping approach, ii) three Italian cities, through a local approach. Mapping CDHs requires gridded values of hourly air temperature. Such gridded data are provided by the WRF model (Weather Research & Forecasting Model 2021), which is a numerical weather model able to simulate past and future weather variables using proper initial and boundary conditions (Section 2.3). The local approach uses the WRF output corresponding to the cells of three cities selected according to the criteria described in Section 2.5.

The analysis covers the period: i) 1st May – 31st October of 2000 and 2019 to study the past trend, ii) the same period of years 2050 and 2080 to study the future trend. In order to consider the variability of climate projections, two different emissions scenarios were considered for the years 2050 and 2080, as described in Section 2.2.

These data could be employed to create an IT tool consisting in an interactive map where the user could read the value of degree-hours corresponding to a cell of the grid. This would correlate climatic data and characteristics of an individual building. Furthermore, furnishing as input the type of cooling systems and the set point temperature, such a tool could supply information about the future variability of energy consumption for cooling.

2.1. Study area

Italy is a nation in Southern Europe, located between the 47th and 36th parallel North. It extends over a length of 1200 kms. The total surface is 302,073 square kilometers (excluding the Republic of San Marino and the Vatican City State). The resident population amounted to 60,359,546 inhabitants at the beginning of 2019. Most of the population (49.0%) lives in the lowland areas, 38.8% in the hilly areas, while 12.2% resides in the mountain municipalities (Italian National Institute of Statistics 2021). 67.7% of municipalities (corresponding to 72.5% of the total surface) belong to the low urbanization class with 42.6% of the total population, 3.4% are highly urbanized municipalities (4.8% of the total surface) with 33.4% of the population and the remaining 28.9% (22.7% in terms of surface) have an average degree of urbanization (ISTAT 2018).

The Italian peninsula is located in the central part of the temperate zone of the northern hemisphere. It is surrounded by the Mediterranean Sea and has a temperate Mediterranean climate, with differences connected to the morphology of the territory characterized as follows: 35.2% of mountains including Alps and Apennines, 41.6% of the hills, 23.2% of plains. According to the Köppen-Geiger classification (Köppen, 1936; Peel, Finlayson & Mcmahon, 2007), Italy contains different types of climates as summarized in Fig. 1 and Table 1. It is affected by the western Atlantic currents during some seasons of the year and by the icy winds from central-eastern Europe in other seasons. The milder summers enjoy the beneficial influence of the Azores anticyclone. When this anticyclone does not settle in the center of the Mediterranean, the southernmost regions are affected by the warm North African anticyclone.

During the year, average temperatures can be summarized as follows:

- Minimum temperatures ranging from −8.8 °C in the North to −2.8 °C in the Center and 0.6 °C in the South, with a national average of about −4.0 °C;
- Average temperatures ranging from 11.6 °C in the North to 14.5 °C in the Center and 15.7 °C in the South, with an average around 14.0 °C;
- Maximum temperatures ranging from 31.6 °C to 32.9 °C in the Center to 34.8 °C in the South, with a national average around 33.1 °C.

2.2. Emissions scenarios for the future climate

In its Fifth Assessment Report (AR5), the Intergovernmental Panel for Climate Change (IPCC) developed four Representative Concentration Pathways (RCPs) describing “four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use” (T. F. Stocker et al., 2013). Unlike the scenarios from the Special Report on Emissions Scenarios applied in previous assessments, the RCPs also consider climate policy impacts. A key parameter in the definition of such emissions pathways is the radiative forcing which refers to the “net change in the energy balance of the Earth system due to some imposed perturbation” (Pinault, 2018). In more detail, the four RCP scenarios are: i) RCP2.6, a “stringent mitigation scenario” in which “radiative forcing peaks at approximately 3 Wm^{-2} before 2100 and then declines”; ii) RCP4.5 and RCP6.0, two “intermediate scenarios where radiative forcing is stabilized at approximately 4.5 Wm-2 and 6.0 Wm-2 after 2100″; and iii) RCP8.5 with very high GHG emissions, where “radiative forcing reaches values greater than 8.5 Wm^{-2} by 2100 and continues to rise for some amount of time” (T. F. Stocker et al., 2013).

In this study, RCP4.5 and RCP8.5 are considered for the projections of future energy needs for the summer cooling of buildings for the reasons described in Section 2.3.

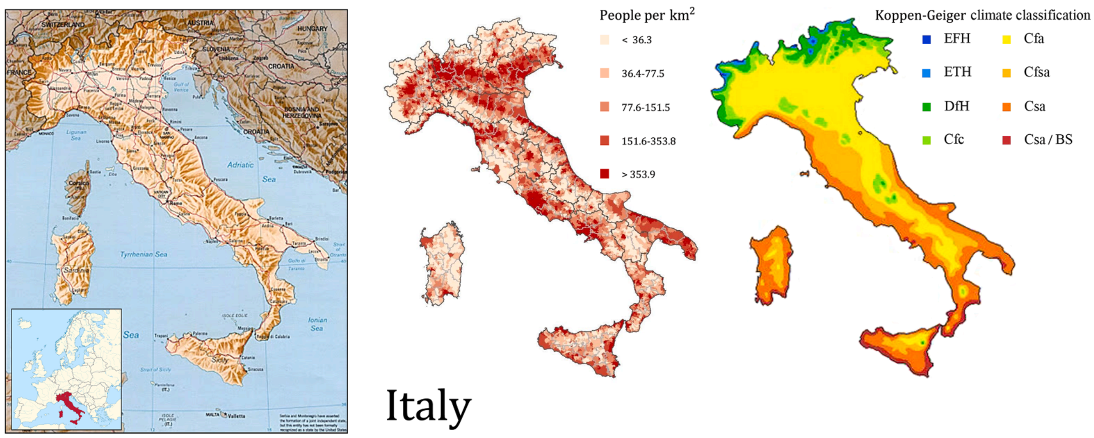

Fig. 1. Map of Italy, population density and Köppen-Geiger climate classes in Italy.

Table 1
Description of Köppen-Geiger climate classes present in Italy.

Köppen-Geiger climate class	Climate class description
Csa tending to BS	Subtropical temperate
Csa	Warm temperate
Cfsa	Transitional temperate
Cfa	Temperate with warm summer
Cfc	Cool temperate
DfH	Cold temperate
ETH	Cold of the tundra
EFH	Permanent snows

2.3. *Use of weather research and forecasting (WRF) model*

Gridded data of air temperature over Italy are simulated both for past and future years through a numerical weather prediction model: the WRF model. WRF is based on fully compressible, Euler non-hydrostatic equations and includes parameterizations of physical processes not explicitly solved. The spatial discretization for the variables in the WRF is based on a staggered Arakawa C type, where the velocity components are staggered one-half grid length from the thermodynamic variables. The technical description of the model can be found in Skamarock et al. 2008 (Skamarock et al., 2008).

The numerical domain over Italy (at 12 km of horizontal resolution) has been nested in the mother domain over Europe (at 36 km of horizontal resolution) through the one-way nesting technique (Skamarock et al., 2008). The vertical resolution is equal for the two domains and decreases from the ground to the top of the domain. In more detail, the vertical grid contains 33 vertical levels with 11 levels below 1000 m, with the lowest one at about 25 m. Both the domains are shown in Fig. 2a. Regarding the physics options, we used the configuration summarized in Table 2 which was already tested and applied over Italy in previous studies (e.g., Falasca and Curci (Falasca & Curci, 2018)). The WRF requires initial and boundary conditions which are provided by suitable datasets. In this study, the dataset "Global Forecasting System (GFS) operational analyses of the National Center for Environmental Prediction (NCEP)" (Tropospheric Analyses 1999) has been used for the simulations for 2000 and 2019, while the dataset "NCAR CESM Global Bias-Corrected CMIP5 Output" (Monaghan, Steinhoff, Bruyere & Yates, 2014) was used for the future years of 2050 and 2080. The latter dataset provides files for three RCP future scenarios (RCP4.5, RCP6.0 and

Table 2
Configuration of the WRF simulations.

Category	Scheme
Microphysics	WSM6
Long wave radiation	RRTMG scheme
Shortwave radiation	RRTMG scheme
Surface layer	Revised MM5 Monin-Obukhov
Land Surface	Unified Noah land-surface model
Planetary Boundary Layer	Bougeault and Lacarrere
Urban physics	Bulk

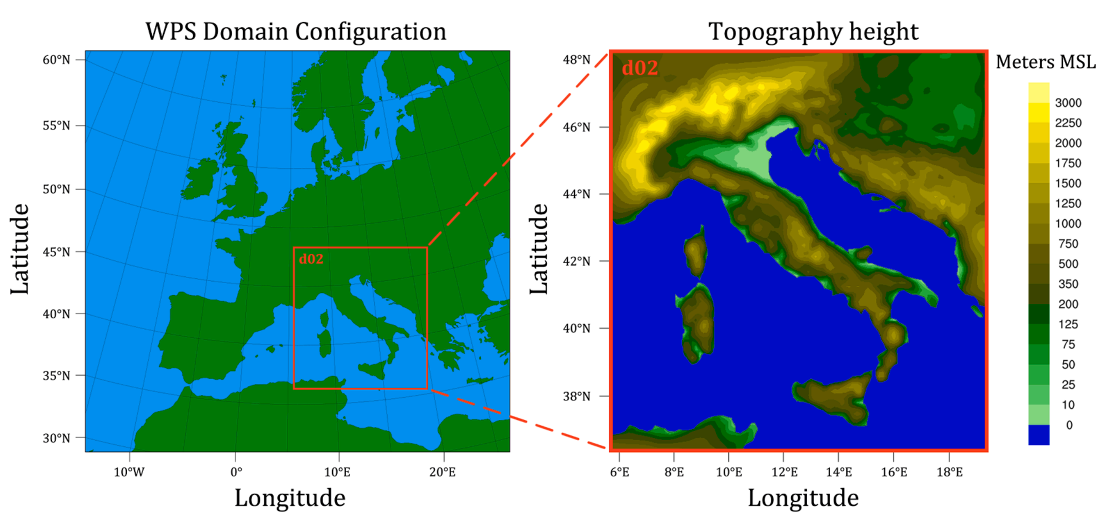

Fig. 2. WRF domains (left) and topography height in the innermost domain (right).

RCP8.5) and the two extreme scenarios RCP4.5 and RCP8.5 have been considered. The simulations performed in this work and the datasets used are listed in Table 3. In order to reinforce confidence in this single-year approach, an analysis of the years chosen (2050 and 2080) and those in the surrounding decades (2045–2055 and 2075–2085) was carried out using the input dataset to WRF. In particular, the intercomparison of the monthly anomalies of 2-m temperature, calculated with respect to the mean of the pertaining decade and averaged over Italy, revealed that 2050 and 2080 do not present particular tendency in positive or negative anomalies, especially in the analyzed period from May to October.

2.4. Quantification of cooling demand

As introduced in Section 1, this study quantifies the cooling demand of buildings by using the cumulative sum of the positive differences between the hourly outdoor temperature and the indoor comfort temperature (equal to 26 °C) (American Society of Heating Refrigerating & Air Conditioning Engineers 2017). These are computed for the cooling season, which runs from May to October period, and are named "Cooling Degree Hours". This metric is a number easy to read and interpret, since it is a common factor for cooling demand of buildings regardless of their geometric and thermo physical characteristics. In particular, the cooling energy needs of the buildings are directly proportional to this quantity. CDHs are also commonly used as an index of severity and duration of climatic events in a specific geographical area and a time interval.

It is mathematically defined as:

$$CDHs = \sum_{h=1}^{n} (T_{out} - 26)_h^+ \tag{1}$$

Where n is the total amount of hours in the simulated time span (i.e., 4416 for May-October). The exponent + means that the summation concerns the hours (h) where the temperature difference is positive and the subscript c stands for "cooling". The quantity of the valid addends of this summation represents the operational hours of the cooling systems. This method requires continuous hourly data for all points of the regular grid used, which are provided by the WRF model.

Cooling Degree Hours are defined similarly to Cooling Degree Days with the difference that the first are based on average hourly temperatures, whereas the latter are based on the average daily temperature.

2.5. Mapping and local approaches

In order to visualize the map of Italy without discontinuity, gridded data were post-processed through a Gaussian process regression. In other words, data were interpolated using "kriging" techniques (Interpolation of Spatial 2020), also called technique of Wiener – Kolmogorov prediction (de Wilde et al., 2011). Kriging is a geostatistical grid method minimizing the mean square error, useful and popular in many fields since it produces visually appealing maps starting from spaced data (Dolinar et al., 2010).

Three Italian cities have been chosen for local studies on the basis of their population and geographical location. In particular, the three cities are located at different latitudes and are very populous. They are: i) Milan (latitude 45,443,405, longitude 9,1073; population of about 1400,000 inhabitants), in the Northern Italy; ii) Rome (latitude 41,936,718, longitude 12,529,785; population of about 3000,000 inhabitants) in the Center of Italy; and iii) Palermo (latitude 38,10,244, longitude 13,122,345; population of about 700,000 inhabitants) in the South. These cities belong to different Koppen-Geiger climate classes: Milan has a Marine West Coast Climate (Cfa), Rome a warm-temperate subtropical climate (Csa) and Palermo a Mediterranean Climate (Csa tending to BS).

Table 3
Summary of the simulations performed in this study.

Years	Initial and boundary conditions	Future scenario	
2000	GFS operational analyses of NCEP (National Centers 2000)	None	
2019	GFS operational analyses of NCEP (Tropospheric Analyses 1999)	None	
2050	NCAR CESM Global Bias-Corrected CMIP5 Output (Monaghan et al., 2014)	RCP4.5	RCP8.5
2080	NCAR CESM Global Bias-Corrected CMIP5 Output (Monaghan et al., 2014)	RCP 4.5	RCP8.5

3. Results

Maps showing values of CDHs across Italy were developed from the outputs of the WRF simulations. Statistical analysis was performed using data of the all grid nodes with both space and time approaches. A local study concerning the three Italian cities is presented.

3.1. Maps of Italy

The amount of hours characterized by an outdoor air temperature higher than 26 °C (i.e., the set-point temperature of the cooling systems (American Society of Heating Refrigerating & Air Conditioning Engineers 2017)) has been computed for each grid node for the whole period simulated. The spatial interpolation method described in Section 2 has been applied to realize the maps in Fig. 3. For each cell, when the air temperature is higher than 26 °C (i.e., the indoor thermal well-being temperature) cooling systems will be operational. The chromatic scale helps to highlight the progressive increase in the magnitude of this temperature, with gray tones turning more intense and dark with the increase in the amount of the operation hours of the systems.

The rise in amount of operation hours of the cooling systems does not necessarily follow the increase of CDHs. Indeed, a high level of CDHs could be due to a few hours of strongly exceeding the reference temperature (26 °C), or low temperature deltas occurring for several hours. For this reason, Fig. 4 shows the levels of CDHs in the Italian peninsula. In this study, areas with growing operation hours coincide with those where CDH levels increase as well.

The spatial distribution of the CDHs (described in Section 2.3) is shown in Fig. 4 through shades of red for the four years (2000, 2019, 2050, 2080) and the two emissions scenarios considered (RCP4.5 and RCP8.5). It is crucial to point out that CDHs depend on both the external temperature (compared to the ignition set point of the systems, 26 °C) and the number of operation hours.

Table 4 lists the median and maximum values reached by operation hours and by CDHs in the simulated cases.

In order to evaluate the spatial distribution and the extent of the variation of CDHs with respect to the past, Fig. 5 shows maps representing CDH differences: on the left, between 2019 (representing the current climate) and 2000 (representing the past climate); on the right, between 2050 and 2080 (representing the future climate) and 2019, for both the emissions scenarios RCP4.5 and RCP8.5. The 2019–2000 difference has positive or null values, implying that energy consumption for cooling has increased everywhere except from the mountains (Alps and Apennines) where CDHs did not change over time. Also the predictions for the future suggest unaltered values along the mountain ridges, while most of the coastal and flat areas of the peninsula will see an increase in CDHs. Positive differences mainly characterize densely populated areas.

All graphs provide information on the time evolution of the annual number of operation hours of the cooling systems and of the CDHs, both in absolute and relative terms. Since CDHs are proportional to the energy needs for cooling, this allows evaluating: i) the energy consumption of the buildings located in the different areas of Italy in the last 20 years; ii) the alteration of the energy consumption in the recent past (i.e., from 2000 to 2019) and in the future (i.e., from 2019 to 2050 and 2080) based

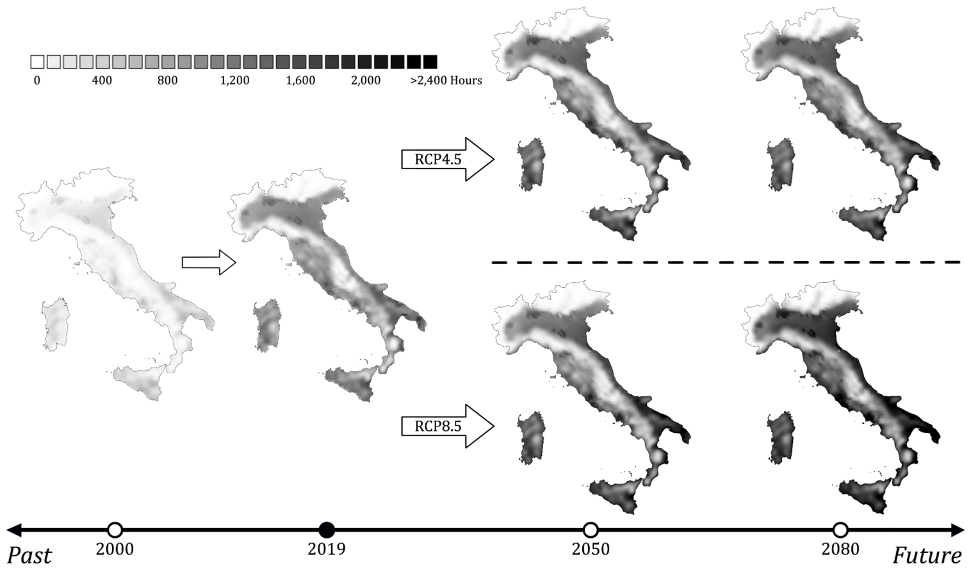

Fig. 3. Maps of the amount of operation hours of the cooling systems (Tair > 26 °C) during the May-October period in 2000, 2019, 2050 (RCP4.5 and RCP8.5 scenarios) and 2080 (RCP4.5 and 8.5 scenarios).

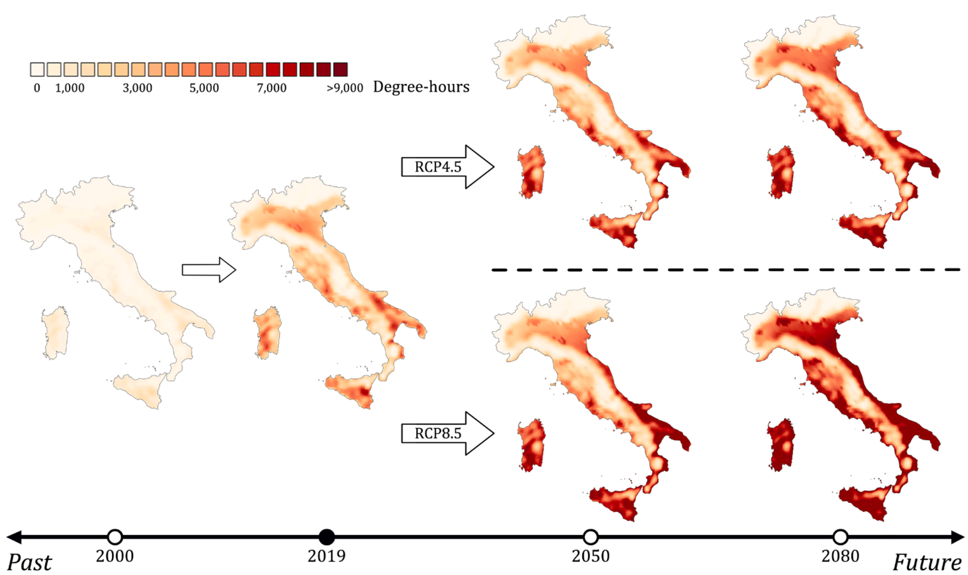

Fig. 4. Maps of CDHs (T_{air} > 26 °C) during the May-October period in 2000, 2019, 2050 (RCP4.5 and RCP8.5 scenarios) and 2080 (RCP4.5 and 8.5 scenarios).

Table 4
Median and maximum values of operation hours and CDHs in the simulated cases.

Case	Median Operation Hours	Maximum Operation Hours	Median CDH	Maximum CDH
2000	135	669	203	1906
2019	858	1935	2503	8121
2050-RCP4.5	1055	2207	3337	11,261
2050-RCP8.5	1098	2568	3521	12,876
2080-RCP4.5	1166	2402	4477	12,912
2080-RCP8.5	1475	2832	6025	15,812

on different climate scenarios.

3.2. Descriptive statistics analyses

Figs. 6-8 show the distribution of CDHs over Italy quantified spatially and temporally. Three types of visualization are applied to investigate the distribution of CDHs for Italy, with gradually increasing detail and from different points of view.

Fig. 6 presents the cumulative distribution. The x axis shows values of CDHs; the y axis shows the percentage (i.e., the occurrence) of grid nodes characterized by CDHs equal to or higher than the corresponding CDH value on the x axis. For example, the abscissa value corresponding to $y = 0\%$ represents the maximum level in Italy. Different years are associated to different colors and the emissions scenarios are further differentiated through the marker. This visualization compares not only the maximum CDHs value of each simulation, but also the CDHs value corresponding to each percentage of cells on the y axis. The slope of the curves also provides relevant information on the evolution of energy

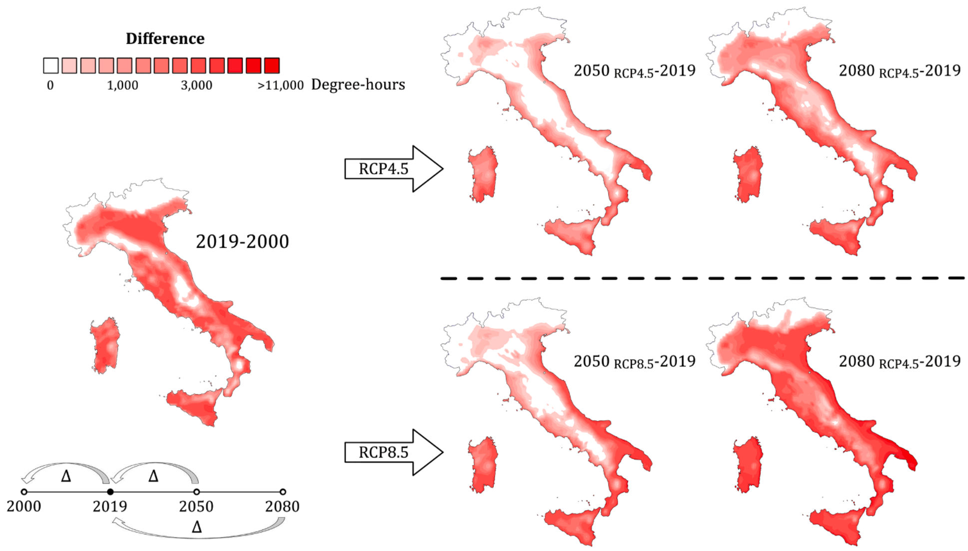

Fig. 5. Maps of CDH differences with respect to 2019 for the simulated cases.

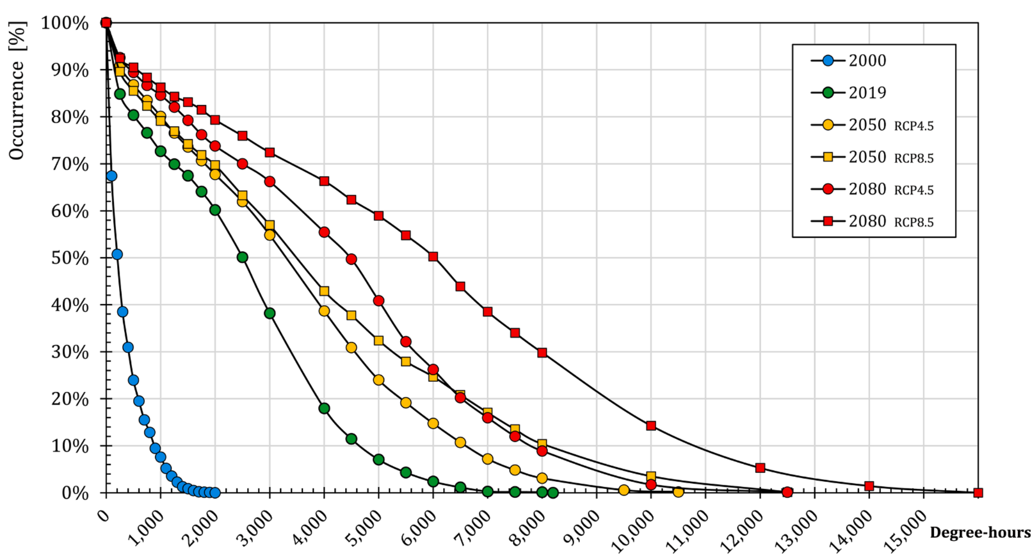

Fig. 6. Cumulative curves of CDHs for the simulated cases in Italy.

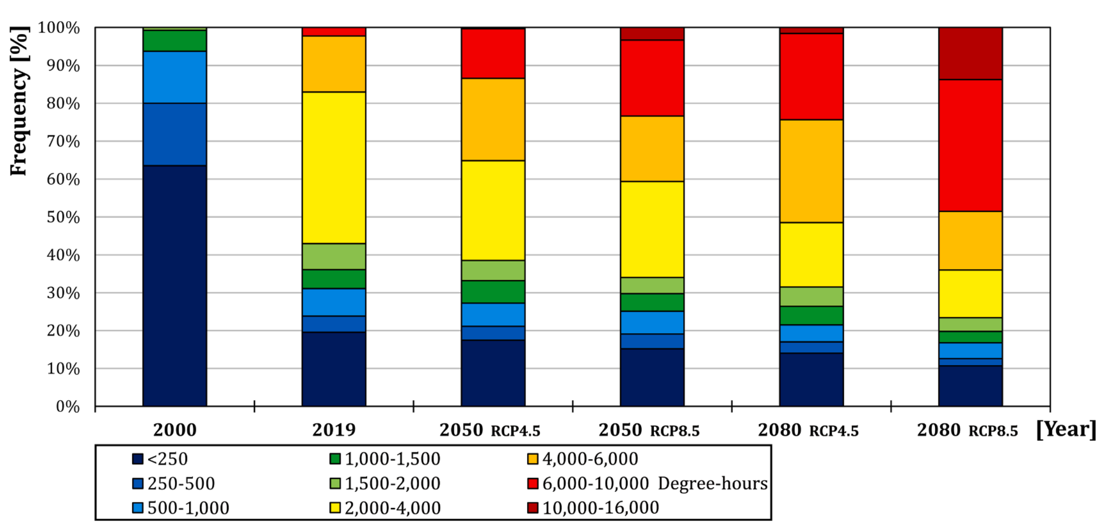

Fig. 7. Frequency analysis of the CDH levels for the entire cooling season in Italy for each case.

demand for cooling. The maximum CDHs value reached in the simulated cases grows from 2000 to 2080, with the 2050-RCP8.5 and 2080-RCP4.5 cases having the same maximum value (equal to 12,400° hours), between that of 2050-RCP4.5 (equal to 10,200° hours) and that of 2080-RCP8.5 (equal to 16,000° hours). The same percentage of data on the y-axis is characterized by a higher CDH level from 2000 to 2080. For example, 40% of the data has CDHs above 200° hours in 2000, while the same percentage has a level above 3000° hours in 2019 and above 7000° hours in 2080 according to the RCP8.5 scenario. Another observation concerns the ratio between the maximum CDHs reached in the different cases: the ratio between the maximum value in 2019 and that in 2000 is equal to about 4, it is 1.2 between 2050-RCP4.5 and 2019 and about 2 between 2080-RCP8.5 and 2019.

From a spatial point of view, it is possible to compute the percentages of nodes characterized by different CDH levels and carry out a frequency analysis for each year (or week) of the year. This is useful to show how: i) the percentage of nodes that have reached certain ranges of values progressively increase over time, ii) certain nodes (and therefore geographic areas) reach definitely high values over time.

Fig. 7 shows the subdivision of the grid nodes over Italy among different CDHs ranges. These ranges have been identified at increasing steps in order to represent the whole CHDs dataset. This demonstrates that: i) the number of nodes reaching high CDHs grows as the climatic conditions of the summer period heats up, ii) the levels will reach definitely high values in some geographic areas (i.e., nodes). For example, the "less than 2050″ range covers more than half of nodes (60%) in 2000 and maximum ~20% in the other cases. At the same time, the upper-intermediate levels (in yellow) that are not touched in the year 2000 cover about 50% in 2019, 2050-RCP4.5 and 2050-RCP8.5. Moreover, according to the pessimistic future scenario (2080-RCP8.5) more than 70% of the Italian territory will be affected by CDH levels never reached in the year 2000.

Since this graph does not provide information on the evolution of CDHs during the simulated seasons, Fig. 8 shows the occurrences in percentages of the degree-hours ranges, summed up for each week of the simulated period (26 weeks in total). It represents the percentage of nodes having a certain level of CDHs each week and the distribution of CDH levels over the May-October period. The range of levels covering the 26 weeks of the cooling season is very wide (from 0° hours to 1800° hours), as shown by the legend of Fig. 8. The chromatic alteration of the graphs indicates that the values reached each week evolve over time. For example, in 2000 most of the data are characterized by the 0–10°-hours level (dark blue) and only a few percentages of nodes present the 200–400° hours (yellow). Conversely, in 2019 and even more in 2050 and 2080 only the starting and closing weeks of the season are colored in dark blue. In particular, in 2080 only the two (for RCP4.5) and three (for

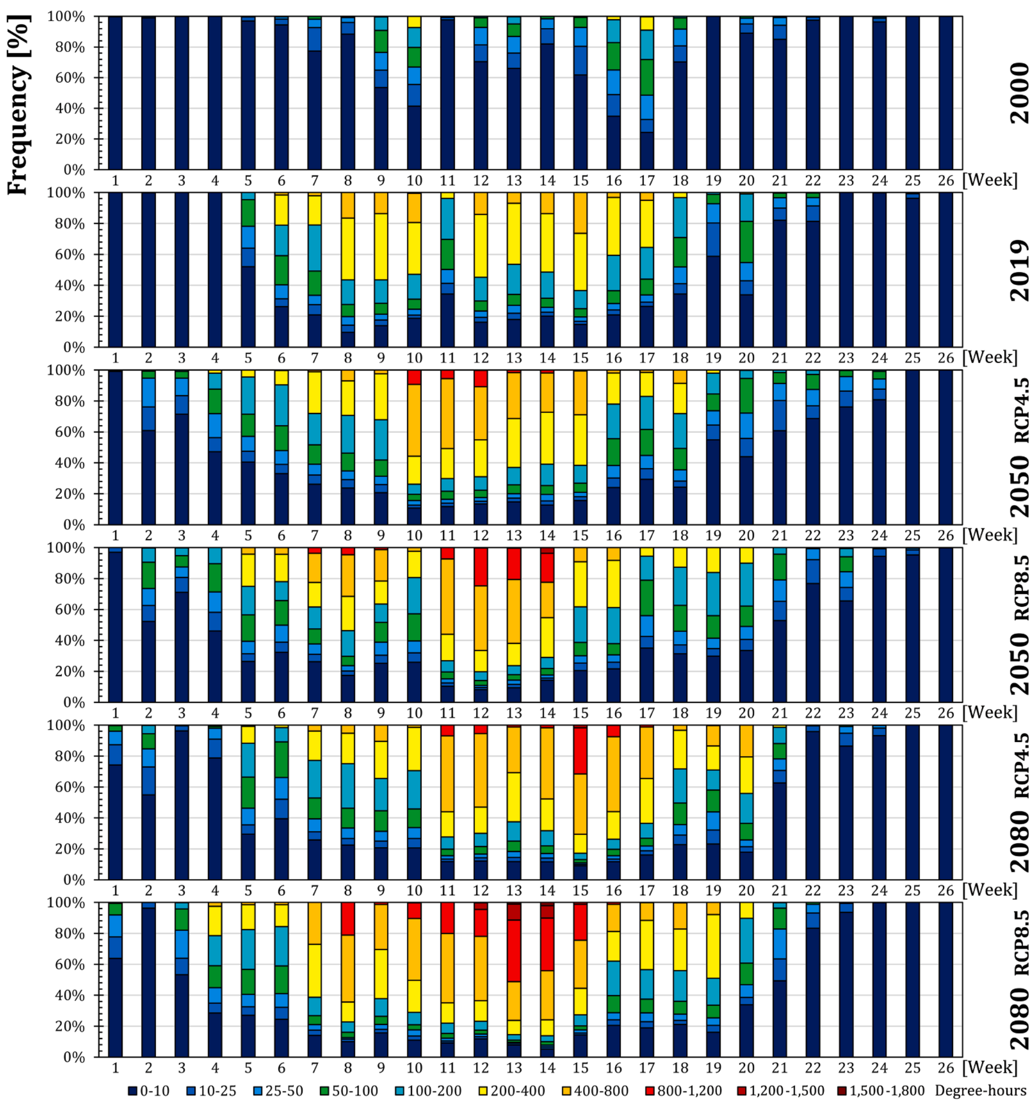

Fig. 8. Frequency analysis of the CDH levels for each week of the cooling season in Italy.

RCP8.5) last weeks of the season are totally dark blue.

3.3. Temporal analysis of three cities

Local results for the evolution of CDHs and the amount of operation hours have been studied for three cities: Milan, Rome and Palermo.

Fig. 9 displays the amount of operational hours (Fig. 9a) and CDHs (Fig. 9b) for the three cities in the simulated cases. Continuous lines represent the 2000–2019 evolution, dash-dot and dashed lines represent the future evolution according to the RCP4.5 and the RCP8.5 scenario, respectively. Furthermore, yellow lines correspond to Milan, red lines to Rome and blue lines to Palermo.

Although the two quantities (amount of operational hours and CDHs) are interconnected, there is no direct proportionality as an increase in CDHs may be due to an increase in operating hours or may also result from temperature differences. The joint analysis of Fig. 9a and Fig. 9b allows examining whether the increase in CDHs is due to the growth in operating hours or in temperature. For example, Palermo (the most southern city) in 2000 had the lowest number of operating hours and CDHs equal to Rome and higher than Milan. This can be due to temperatures reaching higher values in Palermo than in Rome for a shorter time, so the cooling systems will be switched on for a shorter time in Palermo. In 2019 both quantities are lower in Palermo than in the other cities and this is the consequence of a different CDHs alteration over time among the three cities. In particular, in Fig. 9b the red line (Rome) has a steeper slope than the blue (Palermo) and the yellow (Milan), while Palermo has the lowest slope resulting in the lowest growth rate among the three cities in the 2000–2019 period. Starting from 2019, the two scenarios have a different growth rate. Moreover, each scenario shows a change in slope in the 2050–2080 thirty-years compared to the previous time slot, determining multiple intersections among the curves.

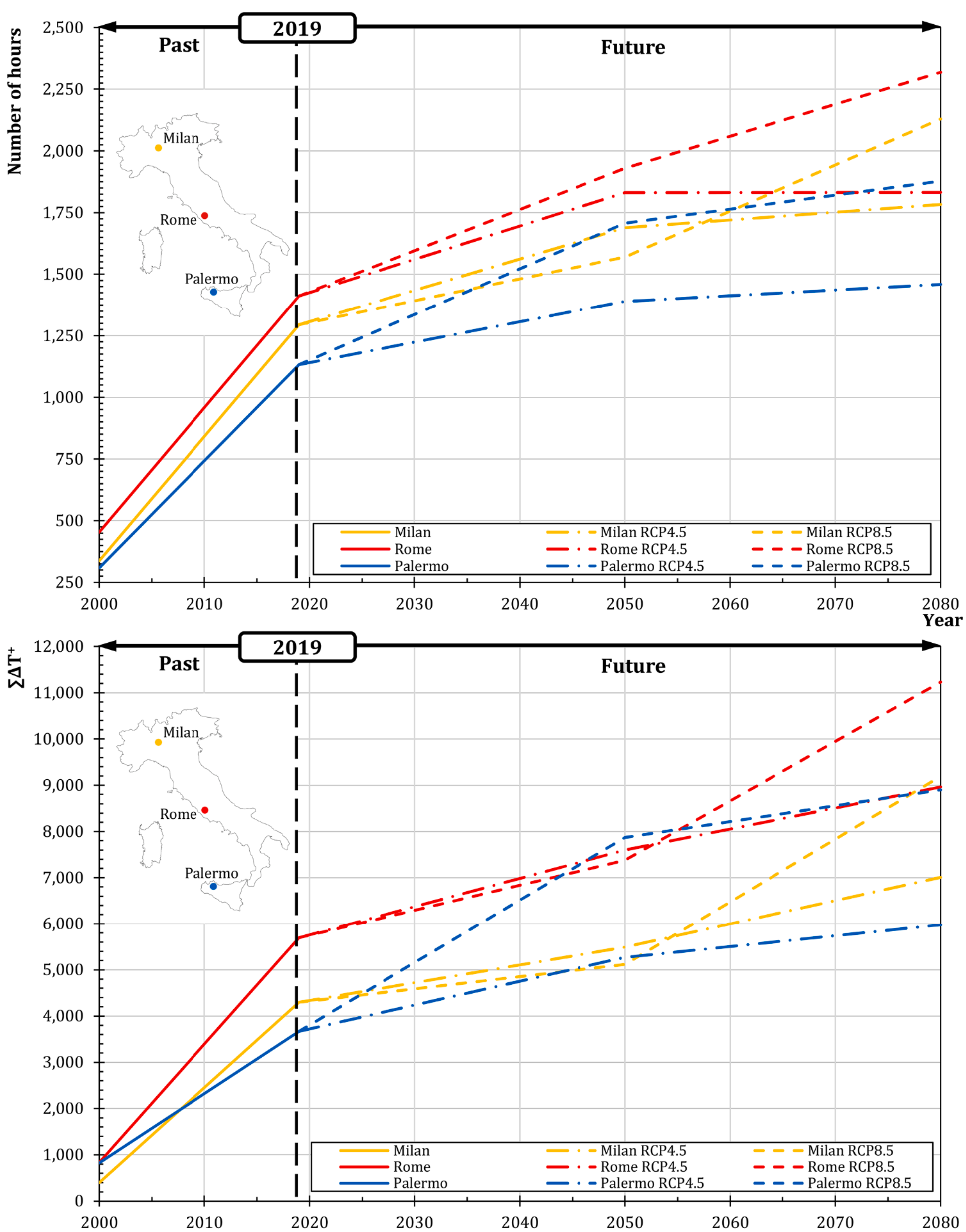

Fig. 9. Evolution of the amount of (a) operation hours and (b) CDH levels over time for three Italian cities: Palermo (blue lines), Rome (red lines), Milan (yellow lines).

4. Discussion

In the Mediterranean area, climate change is already underway and will lead to the intensification of several issues in the coming decades. The climate will be more extreme, with violent manifestations like intense storms (e.g., the recent "medicane" cyclones) or prolonged and torrid heat waves. This could lead to review the climate classification of the entire area in the future. The climate is changing due to anthropogenic activities and the prevailing use of fossil energy sources. Overheating will especially affect the most densely populated areas where more energy will be consumed to maintain thermal comfort conditions. The demand for comfortable indoor conditions leads to an increased adoption of summer air conditioning systems in residential buildings, whereas they were installed only in a few prestigious buildings until a few years ago (in many countries, even among the most developed ones).

As far as Italy is concerned, this trend is recognizable from maps in Section 3.1. Fig. 3 and Fig. 4 show that a generalized warming process occurred over the last two decades (since 2000 to 2019) and that this warming will continue in the future, with the magnitude depending on the emission scenario (RCP4.5 or RCP8.5). The coloring of the maps in Fig. 3 and Fig. 4 reflects the distribution of the population density in Italy, as expected. Indeed, in Fig. 3 and Fig. 4 large Italian metropolitan areas matching with darker spots (black in Fig. 3, red in Fig. 4) are clearly identifiable, such as Milan and Turin in the north, Rome (the capital) in the middle, and Naples in the central south. It is well-known that big cities are afflicted by the urban heat island, phenomenon that exacerbates the effects of the global warming and that is well reproduced by means of WRF simulations (McCarthy, Best & Betts, 2010). Furthermore, in Fig. 3 (and Fig. 4) the geographical areas that turn dark gray (red) and black (dark red) are the Po valley in the North of Italy and the coastal zones in the rest of the peninsula, besides Sardinia and Sicily. Mountain areas (see Fig. 1 and 2) are spared from this increase thanks to their elevation and to their lower population density (Fig. 1). Isolated reliefs are also well noticeable as the main mountain ranges. For example, the peaks of Mount Gennargentu and Etna volcano in Sicily and Sardinia, respectively.

In Fig. 3 and in Fig. 4 it can be observed that the phenomenon of overheating is affecting low-altitude and flat areas since 2000, with the maximum number of operation hours (and CDHs) rising from 669 h (and 1906° hours) in 2000 to 1935 h (and 8121° hours) in 2019. The median values of the two quantities correspondingly increased from 135 h (and 203° hours) to 858 h (and 2503° hours).

This phenomenon intensifies in the South, where some areas show extremely high values. As for future scenarios, maps (Fig. 3 and in Fig. 4) and data (Table 1) show a similarity among 2050-RCP8.5 and 2080-RCP4.5 meaning that an analogous situation will be reached in 2050 according to both the rigid scenario RCP8.5 or in 2080 according to the intermediate emissions scenario RCP4.5. In both cases, large parts of Italy will experience a strong increase in their cooling energy consumption, both in terms of the maximum and median values.

A considerable energy demands in the future will pertain to large Italian areas where a big part of the population lives. The two major islands (Sardinia and Sicily) will be particularly affected by these phenomena, as well as all of southern coastal Italy. Essentially, the entire Italian territory will be affected by an increase in CDHs in 2080 compared to 2019, especially in the RCP8.5 scenario.

In order to not further exacerbate this phenomenon, it will be necessary to moderate this additional energy demand needs by upgrading the energy quality of the building stock, acting on its efficiency and the energy sources (Ciardiello et al., 2020).

The statistical analysis performed here indicates that the maximum level of CDHs has grown more from 2000 to 2019 than it will grow in the future, even under the pessimistic scenario (Fig. 6). Furthermore, the shape and slope of the curves indicate the percentage distribution of CDH levels among the grid nodes. For example, 2080-RCP8.5 has a gentle curve suggesting an almost uniform distribution of CDH levels among the nodes up to the maximum value. This means that the whole Italian territory (even the “colder” mountain areas) will be affected by generalized overheating. On the contrary, the year 2000 is characterized by a very steep curve with few nodes (a percentage of less than 10%) characterized by CDH levels close to the maximum. Starting from 2019, the curves "swell" in their central part producing a change in the direction of curvature gradually more conspicuous over the years and this means that all the nodes show a significant increase in percentage values of CDHs (Fig. 6).

The trend over the years shows growth of the frequency corresponding to higher levels of CDHs (Fig. 7). In terms of a weekly detail, the hottest weeks of the simulated period (corresponding to the months of June, July and August) are characterized by increasing CDH levels and growing percentage of involved nodes (Fig. 8). If red is missing in graphs of 2000 and 2019, it reaches 30% in the 15th week (August) of the 2080-RCP4.5 case. In the most extreme scenario, namely 2080-RCP8.5, the darker shades of red representing the highest levels of the scale (1200–1800° hours) also appear between July and August (weeks 12th −14th). This means that increasingly large regions are affected by higher temperatures that persist longer.

The cooling energy demand of buildings has grown considerably over the last 20 years and this trend is confirmed for the future. During the 1970s, in Italy the peak of electricity demand was mainly related to the needs of the industrial sector (Lam, Wan & Cheung, 2009), while nowadays it is reached in the summer due to the demand for the air conditioning of residential buildings (Huebner, Shipworth, Hamilton, Chalabi & Oreszczyn, 2016). As observed above, graphs based on 2050-RCP8.5 and 2080-RCP4.5 are similar, therefore the consequences of the ongoing climate change seem to be unavoidable, but only delayed in time. For policy makers, this demonstrates that the implementation of environmental policies reducing the emission of greenhouse gasses should not be postponed (Tian et al., 2019).

These graphs also allow for a crude evaluation of the future demand for electricity that will be in charge to the national supply and distribution system for the building sector in the absence of energy efficiency improvement. Fig. 9 shows the amount of hours and CDH levels from 2000 to 2080 (for both scenarios RCP4.5 and RCP8.5) for Milan, Rome and Palermo. For the city of Palermo, operation hours (Fig. 9a) show a similar behavior to CDHs (Fig. 9b); for both quantities, in the 2019–2050 segment the RCP4.5 line is steeper than that of RCP8.5, revealing a sort of saturation, while in the following thirty years the curves of the two scenarios appear to be parallel. In Rome, the line of the operational hours shows a constant growth rate according to RCP8.5 from 2019 to 2080, while RCP4.5 predicts a basically constant trend since 2050. Starting from 2050, CDHs thus grow more according to RCP8.5 than according to RCP4.5. Unlike Palermo and Rome, in the 2019–2050 period Milan is characterized by a higher RCP4.5 slope for both the quantities. On the other hand, starting from 2050 the grow rate is higher according to the RCP8.5 scenario than according to RCP4.5 for operational hours and CDHs. All of the above results in Rome and Palermo having the highest and lowest value of operation hours respectively, in 2050 and 2080 for both scenarios. The only exception is represented by the RCP8.5 scenario in 2050, when Milan has the lowest value of operation hours. In 2080 and according to RCP8.5, Palermo reaches a total of operation hours similar to that of RCP4.5 in Rome and Milan. These results are in disagreement with those presented by Ciancio et al. (V. Ciancio et al., 2020) who found a higher number of operating hours of the cooling plants in Palermo than in Rome and Milan, both in the current and future climate. This discrepancy is due to the differences among the methods: this work is based on climate scenarios (RCP4.5 and RCP8.5) which has been developed by the IPCC more recently than those used in V. Ciancio et al., (2020). Moreover, the WRF (used in this work) properly reproduces the urban heat island characterizing each cities, while EnergyPlus (used in V. Ciancio et al., (2020)) simply employs input weather files of airports, thus neglecting the typical overheating of urban areas (Ciancio et al., 2018).

The same ranking applies to CDHs and the highest future values are simulated for Rome. The change in slope in the 2050–2080 section means that in 2080 Milan and Palermo have almost the same values according to the RCP8.5 scenario. And as already observed, in 2080 (and according to the softer scenario) Rome reached a CDH level (8962° hours) close to that of Milan and Palermo according to the stronger scenario (9191° hours in Milan, 8901° hours in Palermo). Palermo, as a coastal city, evidently has benefited from the mitigation of the effects of the recent climate warming. Conversely, Rome (the most populous and energy-consuming) suffered the most from global warming in the period 2000–2019. Apparently, Rome is not close enough to the coast to enjoy the mitigating effect and at the same time it is affected by a significant urban heat island that exacerbates the impact of climate change.

5. Conclusions

Climate change is underway and is projected to continue its run in the future. Air conditioning of buildings has increased during the recent decades and the energy demand for cooling shows a gradual increase. The cost of such technology is in fact more and more accessible to large sections of the population. Summer air conditioning is almost totally based on the use of saturated vapor compression refrigeration machines electrically powered; therefore, this requires an increase in the electricity production during the summer. Since the electricity sector heavily depends on fossil fuels, this involves also an increase in the emission of greenhouse gasses that worsen the climate change, with an escalation that requires intervention.

In this study, the energy need for building cooling is estimated using cooling degree hours (CDHs). CDHs are computed as the sum of the hourly air temperatures exceeding the set point of the cooling systems (i.e., 26 °C). Outdoor temperatures for Italy are provided by numerical simulations performed though the WRF model. In particular, temperature data are provided on a regular grid with a horizontal resolution of 12 km at 2 m height. The year 2000 was simulated as representative of the past climate, the year 2019 as representative of the current climate and the years 2050 and 2080 as representative of the future climate. Since the climate evolution is estimated on the basis of projections associated to precise anthropogenic emission scenarios, for 2050 and 2080 an intermediate (RCP4.5) and a very high GHG emissions scenario (RCP8.5) have been taken into consideration.

Results of the WRF runs (for each year and scenario) have been used to develop maps of CDHs across Italy, in order to explore the evolution of the energy demand for cooling. Results have then been subjected to statistical analysis of the spatial and temporal distribution of CDH levels on the grid nodes. To look at regional effects, the paper includes the investigation of the amount of operational hours and CDH levels in three Italian cities representative of different geographical positions and climate conditions (Milan, Rome, Palermo).

Both the approaches on national and local scale reveal the greater vulnerability of the flat and coastal areas. Cities already impacted by specific issues (such as Rome which has an important urban heat island) will be particularly affected by the consequences of overheating leading to further cooling energy consumption. Moreover, local conditions will weigh more than geographic location. Thus, Milan (in the north of Italy) will be more overheated than Palermo (located much further south and on the coast), since it is polluted and located in the Po Valley.

Findings show that large parts of the Italian territory including the Po valley (in the north) and coastal areas (in the south) will be affected by significant overheating with the consequent increase of the cooling demand for buildings. Such areas are also the most densely populated and therefore present the greatest presence of buildings to be conditioned.

This study gives out large-scale data in highly inhabited areas which will suffer most from the climate change in the future. This methodological approach can be extended to other nations, completing a framework of wider interest. The scientific community is very committed to this type of study, as it is called to find solutions to climate change and improve the resilience of cities and large-scale energy systems. The public administration and large private companies can find interesting insights from the results of this kind of research to plan large-scale energy optimization interventions on buildings in cities. Those who have to plan energy production can better understand when and where there will be the greatest need for energy for the air conditioning of buildings.

Declaration of Competing Interest

None.

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