Climate change and energy performance of European residential building stocks – A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment

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Climate change and energy performance of European residential building stocks – A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment

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HIGHLIGHTS

- Impacts of climate change on the energy demand and thermal comfort of buildings.
- 13 future climate scenarios with 90 years of hourly data in 38 European cities.
- Long- and short-term variations considering climate extremes and uncertainties.
- Extreme climate events notably affect peak loads and thermal comfort of buildings.
- Cooling demand can increase to 28% on average while heating decrease for 16%.

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ABSTRACT

In recent years, climate change and the corresponding expected extreme weather conditions have been widely recognized as potential problems. The building industry is taking various actions to achieve sustainable development, implement energy conservation strategies, and provide climate change mitigation. In addition to mitigation, it is crucial to adapt to climate change, and to investigate the possible risks and limitations of mitigation strategies. Although the importance of climate change adaptation is well-understood, there are still challenges in understanding and modeling the impacts of climate change, and the consequent risks and extremes. This work provides a comprehensive study of the impacts of climate change on the energy performances and thermal comfort of European residential building stocks. To perform an unbiased assessment and account for climate uncertainties and extreme events, a large set of future climate data was used for a 90-year period (2010–2099). Climate data for 38 European cities in five different climate zones, downscaled by the “RCA4” regional climate model, were synthesized and applied to simulate the respective energy performances of the residential building stocks in the cities. The results suggest that there will be larger needs for cooling buildings in the future and less heating demand; however, there are differences in the variation rates between zones and cities. Discomfort hours will increase notably in cities within cooling-dominated zones, but will not be affected considerably in cities within heating-dominated zones. In addition to long-term changes, climate-induced extremes can considerably affect future energy demands, especially the cooling demand; this may become challenging for both buildings and energy systems.

1. Introduction

During the last century, the human population in urban areas has increased rapidly. Currently, more than 55% of the world’s population lives in urban areas; this percentage is expected to increase to 67% by 2050. In Europe and North America, this number is higher (78% in 2016), and is projected to rise to 81% by 2050 [1]. Rapid urbanization and the subsequent changes in urban density have increased the air pollution and energy consumption in cities [2,3]. Human activities have caused the global surface temperature to increase by 1 °C relative to its

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Table 1
Summary of the recent studies on the impacts of climate change with a focus on building energy performance (HD: heating demand, CD: cooling demand, TC = thermal comfort).

Author	Downscaling approach of GCM	GCM, Scenarios & Years	Building type & Scale	Location	Focus
Sabunas & Kanapickas, 2017 [61]	Statistical (Morphing) By CCWorldWeatherGen	GCM: CMNR CM5, HadGEM2-AO, HadGEM2-ES & IPSL-CM5A-LR, RCP: RCP2.6 RCP8.5 (2020 s, 2050 s & 2080 s)	One residential building, at building scale	Kaunas, Lithuania	HD/CD
Wang et al., 2017 [62]	Statistical (Morphing)	GCM: HadCM3 CESM1, RCP: RCP2.6 & RCP8.5 (2020–2089), SRES:A2	Office buildings, at building scale	5 cities, USA	HD/CD
Shen, 2017 [63]	Statistical (Morphing)	GCM: HadCM3, SRES: A1FI & A2 (2040–2069)	Residential and commercial buildings at building scale	4 cities, USA	HD/CD
Tettey et al., 2017 [64]	Statistical (Morphing)	GCM: HadGEM2, RCP: RCP2.6, RCP4.5 & RCP8.5 (2020 s, 2050 s & 2080 s)	Residential and buildings at building scale	Växjö, Sweden	HD/CD
Hwang et al., 2017 [49]	Dynamical	GCM: ECHAM5/MPIOM, SRES A1B (1979–2003, 2015–2039, & 2075–2099)	Representative building typology for residential building at Urban scale	Plain area in central Taiwan	UHI, TC, &CD
Spandagos C et al., 2017 [65]	Bin Method	RCP4.5 RCP 8.5 for (1983–2005, 2006–2014 & 2015–2044).	Unspecified building type at urban scale	Hong Kong, Seoul & Tokyo	HD/CD
Pierangioli et al., 2017 [66]	Statistical (Morphing) by CCWorldWeatherGen	GCM: COSMO-CLM, RCP: RCP 8.5 (2036–2065 & 2066–2095)	One detached house & one apartment block at Urban scale	Central Italy	HD/CD
Sajjadian, 2017 [67]	Statistical (Morphing) by CCWorldWeatherGen	Unspecified (2011–1080)	Four-story residential buildings at building scale	London, UK	HD/CD & TC
Hosseini et al., 2018 [53]	Statistical (Morphing)	GCM: HadCM3,SRES: A2 (2018–2037)	one-story commercial building at building scale	Montreal, Canada	HD/CD
Cellura et al., 2018 [68]	Statistical (Morphing)	24 GCMs RCP: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (2035, 2065 & 2090)	one-story office building at building scale	15 European cities	HD/CD
Triana et al., 2018 [69]	Statistical (Morphing)	GCM: HadCM3, SRES: A2 (2011–2040, 2041–2070 & 2071–2100)	Representative building typology for social housing at urban scale	2 cities, Brazil	HD/CD
Kotireddy et al., 2018 [70]	Unspecified	G, W, G+, W+ (2050)	Single family building at building scale	The Netherlands	Occupant behavior, investment costs
Jiang et al., 2019 [71]	Statistical (Morphing)	SRES: B1, B2 A2 & A1F1 (2020 s, 2050 s & 2080 s)	Unspecified	Beijing, Chicago, Hong Kong, London	Developing weather files
Burillo et al., 2019 [72]	Unspecified	RCP: RCP4.5 RCP 8.5 (2021–2040 & 2041–2060)	Unspecified building type at urban scale	Los Angeles, USA	Peak ED
Flores-Larsen et al., 2019 [73]	Statistical (Morphing)	GCM: HadCM3, SRES: A2 (2020, 2050 & 2080)	Representative building typology for single family house at urban scale	5 cities, Argentina	HD/CD
Shen et al., 2019 [74]	Statistical (Morphing)	GCM: HadCM3, RCP: RCP2.6, RCP4.5, RCP6.0 & RCP 8.5 (2020–2060)	One residential building & one office building at building scale	2 cities, USA	Building retrofit
Shen J et al., 2019 [75]	Statistical (Morphing)	GCM: HadCM3, SRES: A2 (2020, 2050 & 2080)	One apartment unit in a multifamily building at building scale	Rome & Stockholm	TC
Roshan et al., 2019 [48]	Statistical (Sequential K-	GCM: CanESM2, RCP: RCP2.6, RCP4.5, & RCP8.5 (2020–2050)	Unspecified building type at urban scale	10 cities, Iran	TC
Mata et al., 2019 [23]	Dynamical (RCM: RCA3)	GCM: ECHAM5, CCSM3, CNRM, HadCM3, IPSL, SRES:A1B3 (1980–2100)	Residential buildings at urban scale	4 cities, Sweden	Mitigation, costs
Chai et al., 2019 [76]	Statistical (Morphing)	GCM: CNRM-CM5, RCP: RCP4.5 (2021–2080)	Three-story Office building at building scale	5 cities, China	HD/CD & LCA
Dodoo et al., 2019 [50]	Statistical (Morphing)	SRES: A1B (year2030 & 2050)	Single family building at building scale	Ghana	HD/CD & TC
Moazami et al., 2019 [57]	Dynamical (RCM: RCA4) Stochastic (Meteonorm) Statistical	GCM: CNRM, ICHEC IPSLm & MPIM, RCP: RCP4.5, RCP8.5 (2011–2040, 2041–2070 & 2071–2100)	Commercial reference building models, includes 16 building type models at urban scale	Geneva, Switzerland	HD/CD
Moazami et al., 2019 [77]	Statistical (CCWorldWeatherGen, WeatherShift) Dynamical (RCM: RCA4)	GCM: CNRM, ICHEC IPSLm & MPIM, RCP: RCP4.5, RCP8.5 (2011–2040, 2041–2070 & 2071–2100)	Commercial reference building models, includes 16 building type models at urban scale	Geneva, Switzerland	Robust climate buildings
Perera et al., 2020 [26]	Dynamical (RCM: RCA4) including TDY ECY EWY	GCM: CNRM, IPSL ICHEC, HadGEM & MPI, RCP: RCP2.6 RCP4.5 & RCP8.5 (2070–2099)	Residential building at urban level	30 cities, Sweden	Renewable energy potentials
Haddad et al., 2020 [52]	Dynamically	12 GCMs, SRES:A2 (2060)	Representative building typology for single family house at building scale	Darwin, Australia	HD/CD & Retrofitting
Liu et al., 2020 [78]	Statistical (CCWorldWeatherGen, WeatherShift), Dynamical (RCM: RCA4)	24 GCMs, RCP: RCP4.5 & RCP8.5 (2035 s, 2065 s, & 2090 s)	30–40 story public rental housing at building scale	Hong Kong, China	HD/CD & TC
Machard et al., 2020 [55]	Statistical (Morphing) Dynamical (Regional		Single-floor residential building at building scale	Paris, France	

(continued on next page)

Table 1 (*continued*)

Author	Downscaling approach of GCM	GCM, Scenarios & Years	Building type & Scale	Location	Focus
		11 GCMs, RCP: RCP4.5 & RCP 8.5 (2011–2040, 2041–2070 & 2071–2100)			Regional Downscaling Experiment, HD/CD
Jalaei et al., 2020 [79]	Dynamically	GCM: CanRCM4, RCP:RCP8.5 (2020–2079)	2-story clinic office at building scale	3 cities, Canada	LCA
Ciancio et al., 2020 [58]	Statistical (CCWorldWeatherGen)	HadCM3 for A2 (2050 s, 2080 s)	Representative building typology for residential building at building scale	19 European cities	HD/CD
Troup et al., 2020 [54]	Statistical (WeatherShift)	14 GCMs, RCP: RCP4.5 and RCP 8.5 (2030, 2060 and 2090)	PNNL prototype buildings at urban scale	3 cities, US	HD/CD
Kaboré et al., 2020 [80]	Stochastic (Meteonorm)	SRES: A2 (single year 2080)	Commercial building at building scale	2 cities, France	Urban Cooling Performance, TC
Verichev et al., 2020 [81]	Statistical (CCWorldWeatherGen)	35 GCMs, RCP: RCP2.6 & RCP 8.5 (2020–2035, 2035–2050 & 2050–2065)	Representative building typology for single family house at urban scale	74 cities, Chile	HD/CD
Muñoz González et al., 2020 [51]	Statistical (CCWorldWeatherGen)	GCM: HadCM3 (2018 & 2050)	Three historic building at building scale	Southern Spain	HD/CD & TC
Rodrigues and Eugénio, 2020 [82]	Statistical (CCWorldWeatherGen)	GCM: HadCM3,SRES:A2 (2020, 2050, & 2080)	Representative building typology generated by EPSAP at building scale	16 Mediterranean cities	Ideal U-values for 2050
Larsen et al., 2020 [59]	Dynamical	8 GCMs, RCP: RCP2.6 & RCP8.5 (2010–2050)	Heating degree days (HDD) & cooling degree days (CDD) at country scale	Europe	HD/CD
Adilkhanova et al., 2021 [83]	Hybrid downscaling (dynamic and Statistical)	RCP: RCP8.5 (single year 2095)	Single-zone relocatable building at building scale	6 cities, Kazakhstan	Phase Change Material (PCM), TC
Rysanek et al., 2021 [84]	Statistical (Morphing) 10	RCP: RCP8.5 (2020 s, 2050 s, and 2080 s)	Office building at building scale	Vancouver, Canada	Forecasting thermal comfort
Alhindawi et al., 2021 [85]	Statistical (Morphing)	GCM: HadCM3, SRES: A2, and A1FI (2050 s)	Unspecified building type at urban scale	Chelmsford, England	TC
Li et al., 2021 [86]	Unspecified	RCP: RCP2.6, RCP4.5, & RCP 8.5 (single year 2035)	Monte Carlo building at urban scale Urban	Geneva, Switzerland	CD
Bamdad et al., 2021 [87]	Statistical (CCWorldWeatherGen)	GCM: HadCM3, SRES: A2 (2080)	Representative building typology for office building at building scale	2 cities, Australia	HD/CD

pre-industrial level [4]. As a result, the climate has changed, leading to both long- and short-term variations in climate [5]. At the current emission rates, the average global temperature will rise by 1.5 °C between 2030 and 2052 [6]. A major concern arising from this situation is the increased likelihood of more frequent and stronger extreme events [7]. In Europe, increases are projected for heatwaves with shorter return periods, droughts, wildfires, river and coastal floods, and wind storms [8,9]. Consequently, weather-related disasters may affect approximately two-thirds of the European population annually by 2100 [10,11], risking many lives, especially those among the vulnerable elderly and very young populations.

According to the Paris Agreement, urgent actions are required to reduce greenhouse gases (GHGs) emissions in all sectors to keep global warming below 2 °C (and ideally under 1.5 °C) above the pre-industrial levels [12,13]. In general, responses to climate change include two major approaches: mitigation and adaptation [14]. Mitigation denotes reducing the pace of global warming by decreasing the GHG emissions into the atmosphere [15]. Climate change adaptation involves taking actions to prepare for and adapt to the actual/expected future climate [16]. Failure to address both mitigation and adaptation may lead to severe short-term and/or long-term problems, especially in highly populated cities with multi-complex urban infrastructures and systems [17].

Setting sustainable and resilient energy solutions plays an important role in enhancing climate change mitigation and adaptation in cities [18,19]. In this regard, the role of buildings as the main components of cities is vital, as they induce over 30% of the world's total GHG emissions [20] and account for 32% of the world's total final energy use (which is expected to double by 2050) [21]. In Europe, the most significant proportion of building energy consumption is for heating and cooling, accounting for 70% of the energy consumption of residential building stocks [22]. This highlights the great potential of buildings in regards to contributing to reducing energy consumption and GHG emissions [23]. Moreover, buildings play an important role in increasing the energy flexibility in urban areas, which is vital for increasing the share of renewable generation and reliability of urban energy systems [24,25]. Understanding the future energy demands of buildings and their potential for supporting the energy system requires a thorough assessment of probable future conditions based on high-quality climate data [26].

A considerable number of studies have discussed sustainability and climate change mitigation in buildings; however, relatively less research is available regarding impact assessments of climate change and the corresponding adaptations of buildings, especially at the urban scale, and studies considering high-resolution climate data representing extreme climate events are also relatively rare [27]. This is owing to the major challenges and uncertainties associated with the nature of climate and its stochastic behaviors, which makes predicting the degree and pace of expected warming difficult. This results in multiple future climate scenarios and a massive amount of climate data, making such impact assessments burdensome [28]. Moreover, the slow knowledge transfer from the field of climate modeling to that of energy engineering has delayed the progress of the corresponding research. Although there have been considerable achievements in climate modeling over the past few years, the application of the generated knowledge in energy and building engineering remains limited. This is more visible at the urban or city scale, owing to the challenges that come with such scales (especially for long time periods), along with the amount of details and computation time. It is important to account for the impacts of climate change before implementing critical policies or decision-making; otherwise, they may result in contradictory designs and induce a vicious cycle. For example, retrofitting strategies should be set so as to decrease energy demand without compromising thermal comfort [29], especially when passive or less active solutions are promoted.

Accordingly, there is a need to conduct a detailed impact assessment of climate change while adopting the most advanced climate models to obtain a clearer picture of future climate-energy challenges, and to adopt sustainable and reliable energy solutions. This work provides a detailed picture by conducting an impact assessment of climate change based on the energy performances and indoor comfort of the residential building stocks in 38 European cities over five different climate zones, while considering multiple future climate projections. In particular, 13 future climate scenarios with five different global climate models (GCMs) and three different representative concentration pathways (RCPs) are considered for three 30-year periods: 2010–2039, 2040–2069, and 2070–2190. Energy simulations are performed by modeling 252 buildings over Europe according to the "TABULA" webtools. The energy performances and thermal comfort of the buildings are studied based on considering the required energy demands for space heating and cooling. Such a thorough analysis provides a comprehensive picture of the long- and short-term variations in the energy performances of buildings in Europe, and of their thermal comfort.

This article presents the work in the following four sections. Section 2 provides a background on the relevant research works and a concise review of the field, and describes the contributions of this work to the available body of knowledge. Section 3 briefly explains the methodology, adopted climate datasets, and energy models. The results are discussed in Section 4, focusing on the heating and cooling demands as well as the indoor thermal comfort. Finally, the main findings and concluding remarks are presented in Section 5.

2. Background

Modeling the future energy performance of building stocks in cities can provide valuable information for adapting buildings and energy systems to climate change. This can become a very challenging task, especially because of the lack of detailed information. Fortunately, different approaches and datasets exist for obtaining a reasonable picture. A building stock can be described in terms of archetypes or sample buildings [30]. Archetype buildings are artificially constructed buildings representing a specific category of buildings in the inventory, and are usually divided according to the building type, age, and size [31]. A sample building is an actual building designated for representing the existing inventory based on data obtained from measurements (real case studies) [32]. Both models make it easy to describe and analyze building stocks, even when data availability is limited [33]. Some studies describe the building stocks for cities in European countries based on certain types of sample or archetype buildings, e.g., in France [34], Germany [33,35], Norway [36,37], Sweden [38,39], and the UK [40,41]. Some studies have moved beyond national scale when studying the existing building stocks [42]. For example, the European TABULA project collected data and produced data on existing building stocks in 21 EU countries [43,44]. Moreover, the Building Performance Institute Europe (BPIE) data hub is an open data source providing a good overview of the European building stocks [45].

The thermal comfort and energy performances of buildings are closely connected, as a large amount of energy is used to control the indoor temperature of buildings and make them thermally comfortable environments [46]. Most thermal comfort studies focus on adaptive thermal comfort, whereas a few have considered future climate scenarios (see Table 1). For example, Bienvenido-Huertas et al. [47] used Second Assessment Report (A2) emission scenarios for 2050 and 2080, considered adaptive thermal comfort, and compared energy-saving measures for Mediterranean dwellings. Roshan et al. [48] assessed the impacts of climate change on the thermal comfort of ten cities in Iran and quantified the corresponding adaptation measures, considering three future climate scenarios. Hwang et al. [49] studied the impacts of the urban heat island effect and global warming on residential thermal comfort and cooling energy, based on A1B future climate scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (IPCC SRES). The results showed that the increase in the summer cooling demand is much greater than the decrease in the winter heating demand. Dodoo et al. [50] analyzed the impacts of climate change on the thermal comfort of residential buildings in Ghana using one future climate scenario. Muñoz González et al. [51] studied the impacts of future climate change on the thermal comfort and energy performances of historic buildings in southern Spain using one future climate scenario. In general, most of the available studies are based on a very limited number of climate scenarios, and/or on outdated SRES (IPCC Fourth Assessment Report (AR4) emissions scenarios, e.g., [52] and [53], making the results biased [28].

As mentioned earlier, the applied climate data are an important factor in assessing the impacts of climate change. The available future climate datasets are mostly the results of GCM projections. GCMs use different initial conditions and RCPs to simulate future climates [27]. The spatial resolution of GCMs is approximately 100–300 km^2, which is coarse, and the direct output is not recommended for impact assessment [54]. Therefore, one of the two main downscaling methods, i.e., dynamic and statistical, should be used to downscale the GCM data. The statistical downscaling method (which is a well-known approach is the morphing technique) is the most commonly used approach for synthesizing future weather variables. However, statistical downscaling only reflects changes in the average weather conditions and not the extremes, resulting in an underestimation of the impacts of climate change, and failing to account for unprecedented extreme events [18]. Therefore, it is recommended to use dynamically downscaled weather data, as simulated by regional climate models (RCMs). RCMs provide weather data with appropriate temporal (down to 15 min) and spatial resolution (down 2.5 km^2 or even finer). Owing to the natural variability of the climate system, which makes short-term projections unreliable, it is impossible to plan climate change adaptation strategies based on a limited number of climate scenarios and short-term periods [28]. Therefore, a valid impact assessment of climate change should be based on multiple climate scenarios and long-term periods of 20–30 years.

Some major recent works published after 2017 providing assessments of the impacts of climate change on the energy performances of buildings are listed in Table 1 (all of these studies use weather data with hourly temporal resolution). Most of the studies focused on the energy demand at the building scale, some at the urban scale; only a few considered thermal comfort. Among the 41 studies, 29 (70%) were based on statistically downscaled data, 10 of which were generated by CCWWeatherGen. Nevertheless, CCWWeatherGen is based on only one GCM (HadCM3) and one SRES future scenario (A2); therefore, the uncertainty associated with the scenario and climate model cannot be assessed [55]. Moreover, SRES scenarios represent old IPCC scenarios, and have generally been replaced by RCPs. The remaining 17 studies adopted a morphing method based on integrating the monthly averages. Consequently, information such as daily changes and extreme temperature events (heat waves) were not considered [56]. Furthermore, eight studies (20%) used dynamically downscaled weather data (using RCMs); these have been proven to better represent extreme events [18,57]. Among the reviewed studies, 26 (63%) were at the building scale, and 15 (37%) were at the urban scale. Among the 20 European studies, 10 were at the building scale, of which five considered multiple countries (e.g., [58]). At the urban scale, eight out of 15 studies were in Europe (e.g., [26]), and only one study considered multiple countries and climate regions (i.e., [59]). Therefore, it seems that there remains a limited amount of research on the impacts of climate change on building stocks at the country or regional scale, including the different European climate regions and considering the most recent climate models, with suitable temporal and spatial resolutions.

As discussed above, most of the available studies assessing the impacts of climate change on buildings were based on using statistically downscaled climate data sets unable to represent extreme events, and/or on a limited number of future climate scenarios and/or IPCC AR4 climate scenarios (moreover, considerable differences exist between the

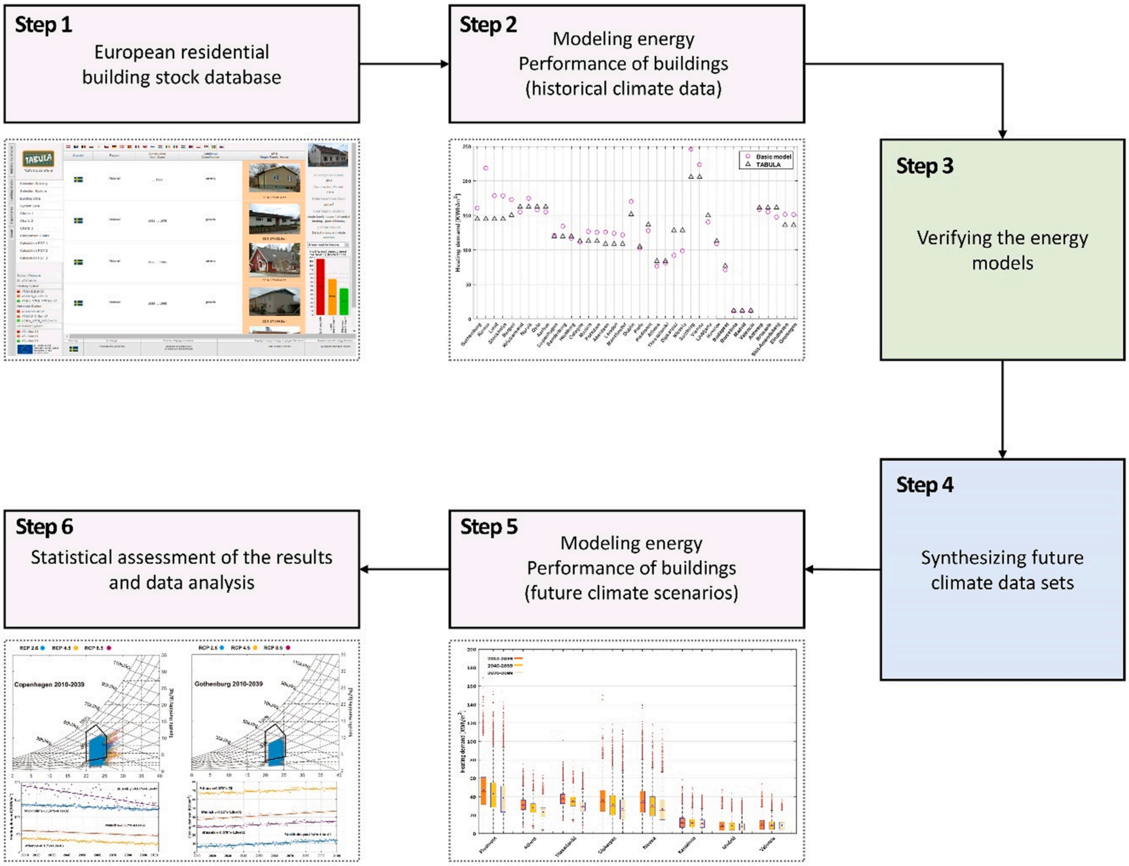


Fig. 1. The workflow of the research.

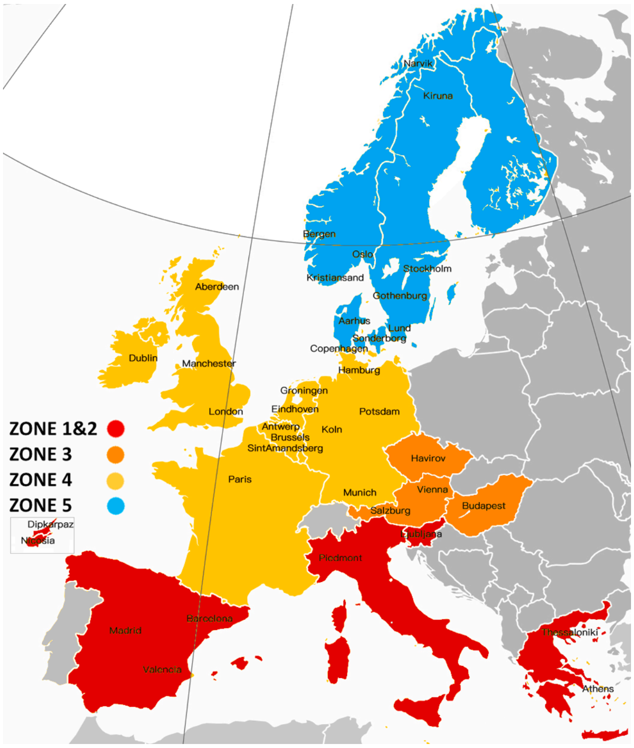


Fig. 2. The five climate zones and 38 cities in Europe considered in this work.

Fifth Assessment Report (AR5) and AR4 climate projections [60]). There are only a limited number of studies on climate change considering multiple countries and their building stocks. Moreover, there are no studies on the energy performances of European building stocks and their thermal comfort levels considering the different climate regions over Europe and multiple climate scenarios, much less using high-resolution RCMs based on IPCC AR5 climate scenarios.

3. Methodology

This work is based on performing numerical energy simulations for building stocks in 38 European cities, considering 13 different future climate scenarios. The workflow of the study includes six steps, as shown in Fig. 1, and the major parts are described in more detail below.

1) Gathering data on European residential building stocks using the TABULA webtools, "EPISCOPE" and other relevant sources.
2) Modelling the energy performance of buildings in IDA Indoor Climate and Energy (IDA ICE).
3) Verifying the energy models for past climate data.
4) Synthesizing future climate data sets for the purpose of this work.
5) Modelling the energy performances of buildings for future climate scenarios.
6) Providing statistical assessments of the results and data analysis, focusing on heating/cooling demands and indoor thermal comfort.

3.1. Case studies and climate zones

The cities and climate zones considered in this work were grouped based on European climate zones and bioclimatic design requirements

Table 2
The average heating demand for residential buildings in the European countries according to TABULA and cooling demand from European project.

Country	City	Heating demand (KWh/m^2)	Cooling Demand (KWh/m^2)
Austria	Salzburg	205.21	38
Belgium	Sint-Amandsberg	160.9	23
Cyprus	Nicosia	128.1	65
Czech Republic	Havířov	112.5	29
Denmark	National	119.3	13
France	Paris	104.5	32
Germany	Potsdam	112.5	33
Greece	National	83.5	66
Hungary	Budapest	76.5	46
Ireland	Dublin	151.3	0
Italy	Piedmont region	136.1	51
Netherlands	National	135.7	16
Slovenia	National	149.5	43
Spain	Valencia	11.6	59
Sweden	National	144.5	21
United Kingdom	National	108.3	21

[88]. The requirements considered the comfort associated with different climate zones, indoor climate, heating, cooling, and daylight. The division of zones was based on the nearly zero-energy buildings (NZEB) climate zones, and combined the Köppen-Geiger classification [89] with the European Heating Index and European Cooling Index from the bioclimatic design requirements. The NZEB climate zone divides Europe into five zones: Zones 1 and 2 (Spain, Italy, Greece, Cyprus, and Slovenia), Zone 3 (Austria, Czech Republic, and Hungary), Zone 4 (UK, Ireland, Netherlands, Belgium, and France), and Zone 5 (Sweden, Norway, and Denmark). The selected 38 cities in this study were based on both the Köppen-Geiger classification and NZEB climate zones. For example, in the NZEB climate zones, Munich and Berlin belong to the same climate zone. However, in the Köppen-Geiger classification, Hamburg belongs to Cfb (temperate climate without a dry season and warm summer), and Munich belongs to Dfb (cold climate without a dry season and warm summer). Similarly, Madrid in Spain belongs to Bsk (arid cold steppe climate) in the Köppen-Geiger classification, whereas Barcelona belongs to Csa (temperate climate with a dry and hot summer) [90]. The climate zones and cities are shown in Fig. 2.

3.2. Future climate data sets

Future climate scenarios are simulated using GCMs. Generally, GCM outputs do not have suitable temporal and spatial resolutions for energy simulations, and require either dynamical or statistical downscaling [91]. As thoroughly discussed in previous works by the authors, the dynamically downscaled weather data generated by RCMs provide a physically consistent representation of climate parameters, as well as extreme weather events [57]. Therefore, the RCM outputs were used and synthesized for this study. Methods for generating future weather datasets have been thoroughly discussed and reviewed in some previous works, for example, [28,57].

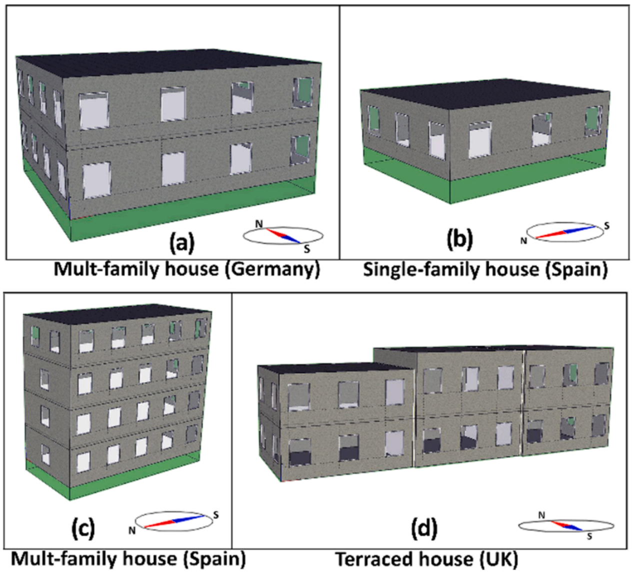
The "Coupled Model Intercomparison Project 5" (CMIP5) was established under the World Climate Research Programme (WCRP) as a continuation of a standard experimental protocol for studying the outputs of coupled atmosphere–ocean general circulation models. The CMIP5 data were dynamically downscaled to the regional scale using the "Coordinated Regional Climate Downscaling Experiment" (CORDEX) which was also used in this work [92]. The climate data used in this work were synthesized using RCA4, i.e., the fourth generation of the Rossby Centre RCM, with a spatial resolution of 12.5 km and temporal resolution of 15 min [28]. Five GCMs were considered in this work: Centre National de Recherches Météorologiques Climate Model 5 (CNRM-CM5), Irish Centre for High-End Computing model (ICHEC-EC-EARTH), Institut Pierre Simon Laplace model (IPSL-CM5A-MR), Met Office Hadley Centre model (MOHC-HadGEM2-ES), and Max Planck Institute model (MPI-ESM-LR) (for details, see [28;26]). The GCMs are forced by three RCPs: RCP 2.6, RCP 4.5, and RCP 8.5. The RCPs are the GHG concentration trajectories used by the IPCC in the AR5 [93]. These scenarios provide numerical information in W/m^2 for future radiative forcing. If the GHG emissions increase, the radiative forcing will increase. RCPs are named after the radiation level, i.e., reaching 2.6, 4.5, 6.0, or 8.5 W/m^2 in 2100 [94]. Each individual RCP represents a larger set of scenarios, and scenarios have been developed to describe the existing uncertainty regarding future emissions. RCP 2.6 provides the lowest possible carbon dioxide emissions in the future, whereas RCP 8.5 is an extreme case, with GHG emissions at three times higher than the current atmospheric level at the end of the century. RCPs 4.5 and 6.0 are milder emission scenarios; in RCP 6.0, the GHG emissions will reach their highest level in 2060, at 75% higher than today, and then will drop 25%. In RCP 4.5, the GHG emissions will increase slightly and reach a peak in (approximately) 2040 [95].

Among the considered GCMs, ICHEC-EC-EARTH, MOHC-HadGEM2-ES, and MPI-ESM-LR are forced by RCP 2.6, RCP 4.5, and RCP 8.5, whereas the other two GCMs are only forced by RCP 4.5 and RCP 8.5. In this study, in total, 13 future climate scenarios over three 30-year periods, i.e., 2010–2039 (near-term or NT), 2040–2069 (medium-term or MT), and 2070–2099 (long-term or LT) with hourly temporal resolution were studied for each city. This enabled us to investigate the evolution of climate variations over time and to cover a large range of probable future conditions, including extremes. In other words, for each building (in each city) and each time period (NT, MT, or LT), 390 years of RCM weather data with hourly temporal resolution were used in the energy simulations. This resulted in massive datasets covering a wide range of future climate conditions, and representing both the long-and short-term variations in climate. Such an arrangement enabled us to perform a non-biased impact assessment of climate change without neglecting climate uncertainties and extreme weather events. Additional details regarding the synthesis of the weather datasets are available in [28] and [91].

3.3. The European residential building stock

To model the building stocks, the TABULA webtool database was used in this study. TABULA provides information on the physical characteristics of buildings in 16 European countries [96]. It provides a classification scheme that includes the physical characteristics of buildings, such as the sizes of roofs, walls, windows, and conditioned floor areas, as well as the corresponding U-values for different construction periods [97,98]. Moreover, TABULA includes quantitative data for determining the representative building types and number of buildings. For example, in the case of Germany, buildings are classified into six types (see Table A.1 in the Appendix). The building roof area of a single-family house (SFH) I in Germany is 105.2 m^2; the heated floor area is 87.2 m^2, the external wall area is 143.5 m^2, and the total window area is 27.2 m^2. A reasonable house model can be established with a length of 10.93 m, width of 8 m, height of 3.07 m, and 12 windows (2.5 m^2 each). For each type of building, TABULA presents the heating demand in KWh/m^2 (e.g., 164.3 KWh/m^2 for the building type SFH I in Germany).

TABULA mainly focuses on the energy demands for residential heating and domestic hot water, and does not consider the energy demands for cooling, air conditioning, lighting, and appliances [44]. The required data were obtained from the reports of several European projects, such as those published by Insitut Wohnen und Umwelt [96], "STRATEGO" (Halmstad University) [99], Policies to Enforce the Transition to Nearly Zero Energy (ENTRANZE) [100], and BPIE [45]. The average heating demands for specific cities as obtained from



Mult-family house (Germany) Single-family house (Spain)

Mult-family house (Spain) Terraced house (UK)

Fig. 3. Example of different housing types.

TABULA and the estimated cooling demands are shown in Table 2 (for additional details regarding the heating and cooling demands of the residential building stocks, the readers are referred to [99]). Notably, detailed calculation data are available for some specific cities in each country or on the national scale, representing the average heating and cooling demand over the entire country.

3.4. Building energy models and indoor comfort

The energy performances of buildings and their indoor comfort were numerically simulated using the IDA ICE software developed by EQUA [101] and verified by the Swiss Federal Laboratories for Materials Testing and Research [102] and further tested and validated with respect to ASHRAE standard 140-2004 [103]. The energy modeling began by establishing a model in IDA ICE for each type of building existing in the TABULA database, while ensuring that the sizes and U-values of the building models were the same as those provided by TABULA. Fig. 3 shows an example of different housing types from TABULA, as generated by IDA ICE. These models became our base case models, and were verified against the reference energy demand values (Table 2) for the past climate using typical meteorological year (TMY) weather files for the corresponding city. TMY data comprises a one-year set of hourly values, including different climate variables representing the most typical months over a 30-year period, usually based on past (observed) climate conditions [104] (the TMY data is hereafter referred to as “past climate“).

Although many residential buildings in Europe do not have cooling systems installed, it is important to investigate the need for cooling in the context of climate change. Therefore, the cooling demand was calculated based on the following formulas, and on setting the maximum cooling capacity according to Table 3 for each building type.

$$V_{air}\ [m^3/s] = Floor\ \ area \cdot 0.35[l/s \cdot m^2] + 7[l/s] \cdot person \tag{1}$$

$$M[kg/s] = \rho_{air}[kg/m^3] \cdot V_{air}[m^3/s] \tag{2}$$

$$Q[kW] = M[kg/s] \cdot \Delta\Delta h[kJ/kg] \tag{3}$$

The supply air volumetric flow rate was calculated based on the Swedish “Boverkets building regulations“ standard [104,105], according to Eq. (1). According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1-2007 [106], the occupancy was assumed as one person per 20 m^2, and ρ_{air} was equal to 1.2 kg/m^3. The cooling capacity was calculated by finding Δh (enthalpy difference) on a psychrometric chart with the outdoor temperature, i.e., at 29 °C and 60% relative humidity, to maintain the indoor temperature at 24 °C and 60% relative humidity, then multiplying by the mass flow rate, according to Eq. (2) [107]. A hybrid cooling strategy was adopted, which implied a combination of natural and mechanical cooling. When the indoor temperature was above 24 °C and the outdoor temperature was below 24 °C, natural ventilation was used, by simply opening the windows. If the indoor and outdoor temperatures were above 26 °C, the windows were closed, and the mechanical ventilation system was engaged. For the heating demand calculations, the maximum heating capacity was set by the IDA ICE itself, thereby providing indoor comfort for the tenants over time.

The verified building models were used to simulate the future performances of buildings in 38 cities, considering 13 future climate scenarios and three 30-year periods (resulting in 788400 h of simulation for each city). This means that when we perform statistical analysis of the results, 390 years of data are considered for each 30-year period and city.

3.5. Indoor thermal comfort

Many factors determine thermal comfort [108], such as personal factors (e.g., clothing insulation and metabolic heat) and environmental factors (e.g., air temperature, radiant temperature, and humidity) [109]. This study was confined to the environmental factors affecting indoor thermal comfort, and the other aspects were not considered.

Table 3
The maximum cooling capacity for each building type (AB: apartment block - SFH: single-family house - MFH: multi-family house - TH: terraced house).

Country	SFH1 (W)	SFH2 (W)	SFH3 (W)	MFH1/ AB1 (W)	MFH2/ AB2 (W)	MFH3/ AB3 (W)	TH1 (W)	TH2 (W)	TH3 (W)
Austria	2000	1900	1680	5040	4500				
Belgium	1226								
Cyprus	1008	1008	1012	1800	1800		502	502	
Czech Republic	2000			8000	8400	4500	4700		
Denmark	2135	2140	2268	8232	6434	6602			
France	2341	2520	4116	8233	8450	8720	8123	8212	8533
Germany	1764	1831	1495	2906	5090	5006			
Greece	1965	2133	2167	4821	3981	3141			
Hungary	1293	2452		5930	7291	7879			
Ireland	1688	1555	1874	766	799	1176			
Italy	1260	2083	2217	10,052	6770	6226	3124	1612	1612
Netherlands	1293	1260	1159	12,247	9844	8441	1310	975	
Norway	1411	1411	2688	5107	7761	8265	2268	2049	2738
Slovenia	2234	2301	2284	4687	5997	11,037			
Spain	2536	2536		15,792	22,764				
Sweden	1780	1780	1780	10,260	10,260	10,260			
United Kingdom	1881	1513	1386	1066	932	929	873	823	756

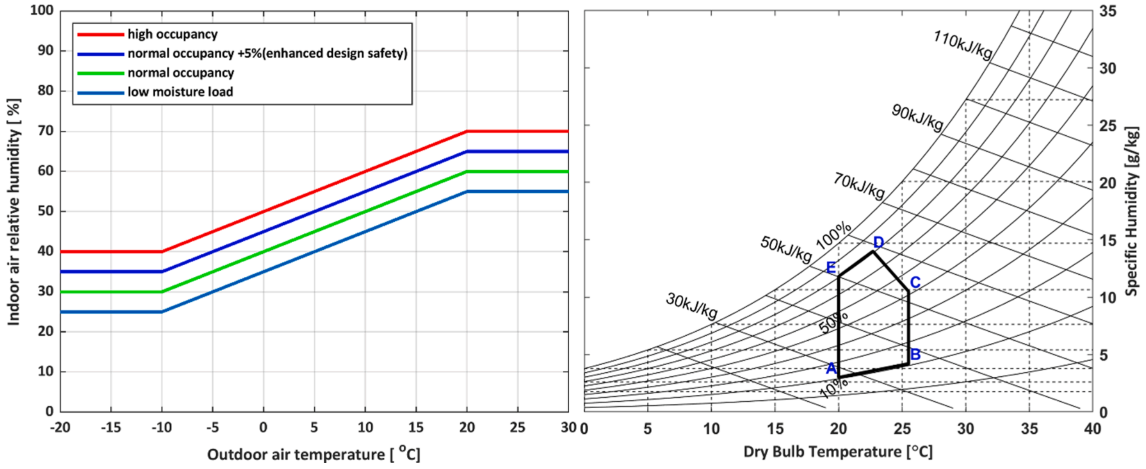


Fig. 4. Indoor relative humidity from outdoor temperature (WTA6-2 2013) and Givoni building bioclimatic chart.

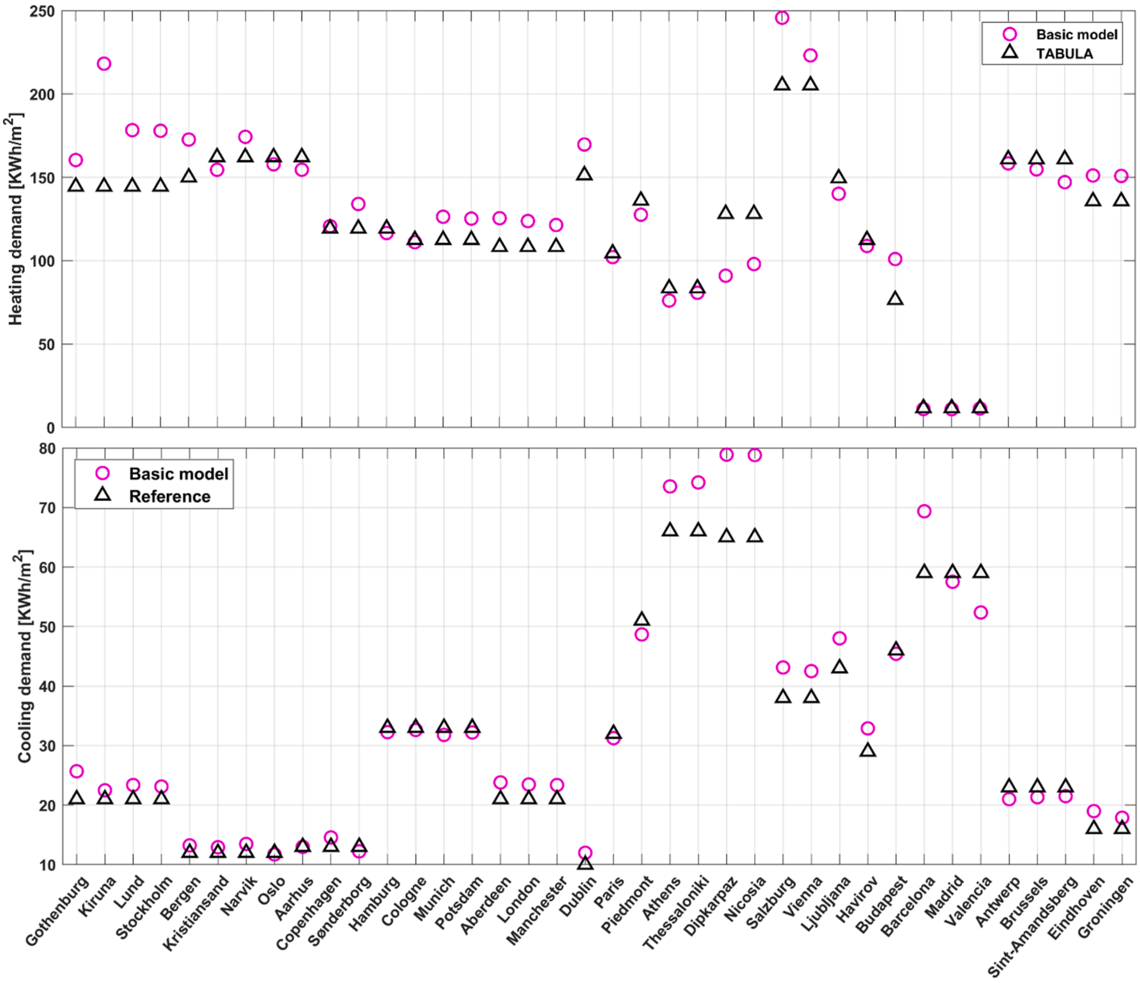


Fig. 5. Comparison of the annual average of heating and cooling demand between the IDA ICE models (using TMY weather data) and TABULA reference cases and EU report reference cases for each city.

The ideal comfort zone was developed by Baruch Givoni (building bioclimatic chart; see ABCDE zone in Fig. 4 right) as an improved version of the ASHRAE comfort zone [110]. This was used to quantify the variations in comfort levels for different cities, buildings, and periods. The ideal comfort zone was defined as the optimal thermal condition under which the body's heat balance could be maintained with minimal additional effort [111]. Therefore, the relationship between the outdoor and indoor climate distributions could be determined based on the projection points on the psychrometric chart. The main reason for using the Givoni comfort zone was that the ASHRAE comfort zone is mostly feasible for buildings with mechanical ventilation systems, whereas many European residential buildings use only natural ventilation.

Two parameters were used to plot the psychrometric chart: the

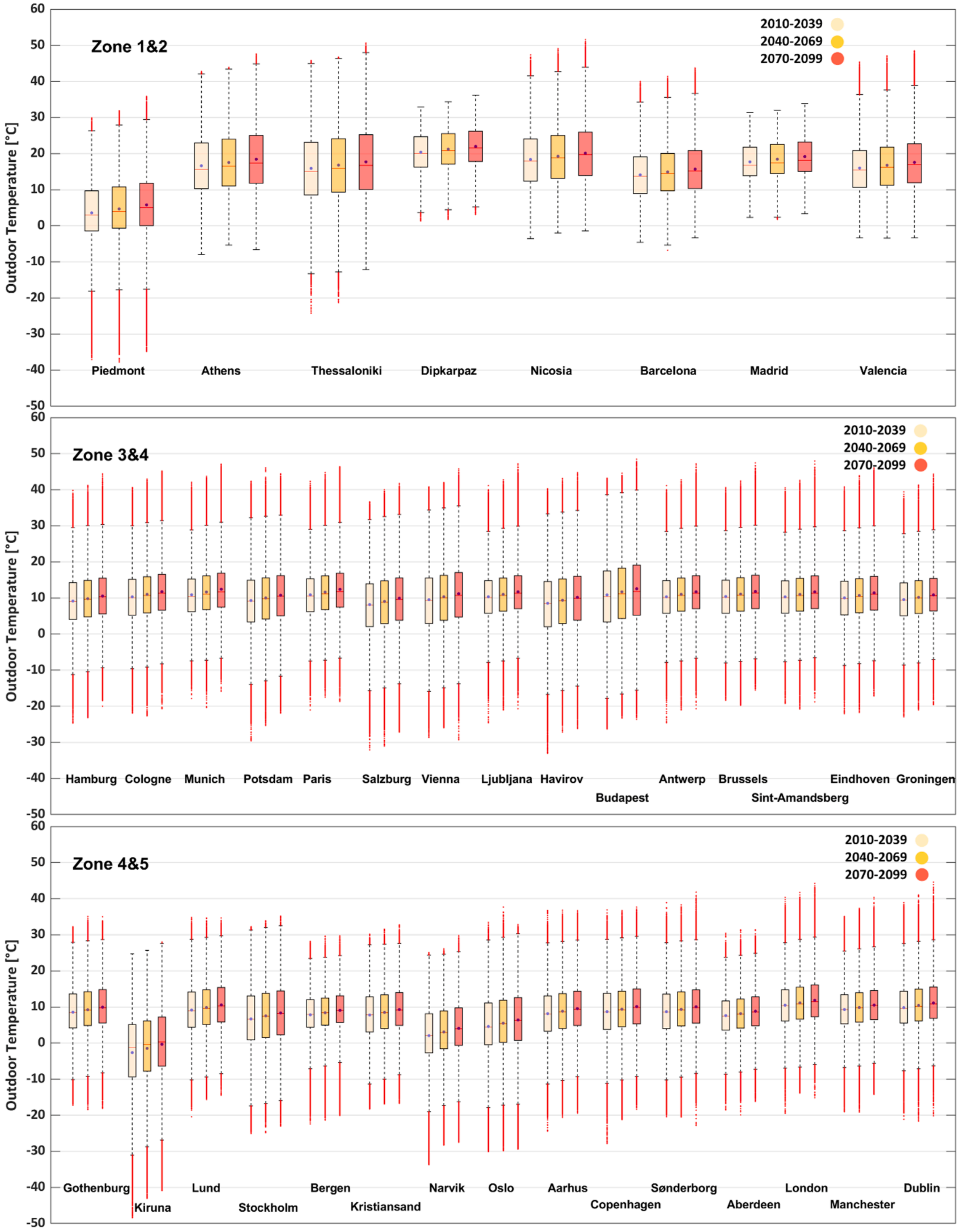
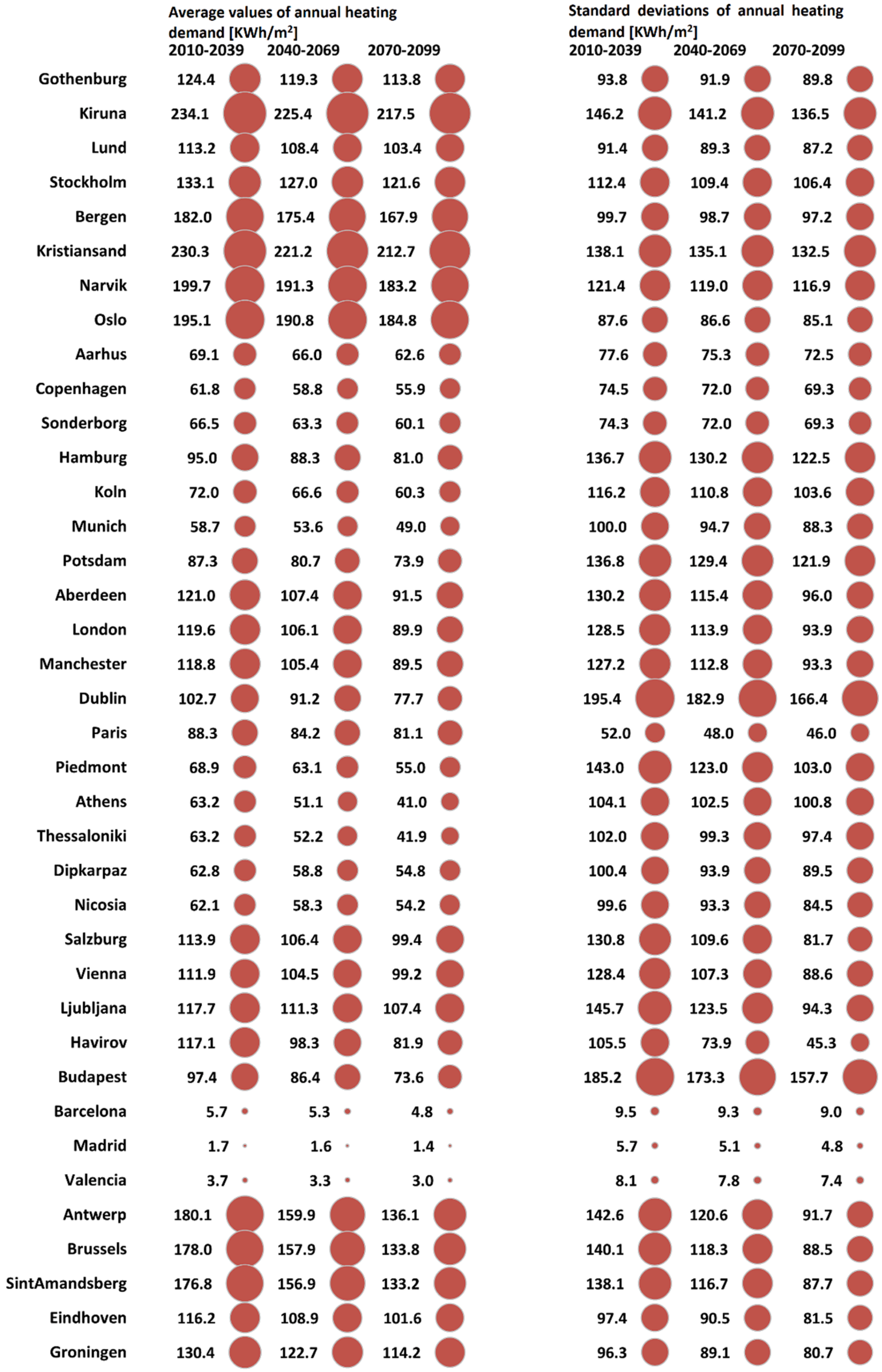


Fig. 6. Outdoor temperature distribution for cities in zone 1–5.

indoor temperature and specific humidity (or moisture content) [112,113]. The indoor temperature was obtained from the IDA ICE simulation results, whereas the specific humidity was calculated based on the indoor temperature and relative humidity. The relative humidity was calculated according to the WTA 6-2 guideline (2013), which provides a simplified method for determining the indoor relative humidity as a function of the outdoor temperature for a normal occupancy level (Fig. 4, left) [114,115].

4. Results and discussion

This section discusses the energy and thermal performances of buildings, and the impacts of climate change on them. Section 3.1 discusses the energy model verification. The heating and cooling demands of buildings for future climate scenarios are discussed in Section 3.2, followed by an indoor thermal comfort analysis in Section 3.3.



	Average values of annual heating demand [KWh/m²]			Standard deviations of annual heating demand [KWh/m²]		
	2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
Gothenburg	124.4	119.3	113.8	93.8	91.9	89.8
Kiruna	234.1	225.4	217.5	146.2	141.2	136.5
Lund	113.2	108.4	103.4	91.4	89.3	87.2
Stockholm	133.1	127.0	121.6	112.4	109.4	106.4
Bergen	182.0	175.4	167.9	99.7	98.7	97.2
Kristiansand	230.3	221.2	212.7	138.1	135.1	132.5
Narvik	199.7	191.3	183.2	121.4	119.0	116.9
Oslo	195.1	190.8	184.8	87.6	86.6	85.1
Aarhus	69.1	66.0	62.6	77.6	75.3	72.5
Copenhagen	61.8	58.8	55.9	74.5	72.0	69.3
Sonderborg	66.5	63.3	60.1	74.3	72.0	69.3
Hamburg	95.0	88.3	81.0	136.7	130.2	122.5
Koln	72.0	66.6	60.3	116.2	110.8	103.6
Munich	58.7	53.6	49.0	100.0	94.7	88.3
Potsdam	87.3	80.7	73.9	136.8	129.4	121.9
Aberdeen	121.0	107.4	91.5	130.2	115.4	96.0
London	119.6	106.1	89.9	128.5	113.9	93.9
Manchester	118.8	105.4	89.5	127.2	112.8	93.3
Dublin	102.7	91.2	77.7	195.4	182.9	166.4
Paris	88.3	84.2	81.1	52.0	48.0	46.0
Piedmont	68.9	63.1	55.0	143.0	123.0	103.0
Athens	63.2	51.1	41.0	104.1	102.5	100.8
Thessaloniki	63.2	52.2	41.9	102.0	99.3	97.4
Dipkarpaz	62.8	58.8	54.8	100.4	93.9	89.5
Nicosia	62.1	58.3	54.2	99.6	93.3	84.5
Salzburg	113.9	106.4	99.4	130.8	109.6	81.7
Vienna	111.9	104.5	99.2	128.4	107.3	88.6
Ljubljana	117.7	111.3	107.4	145.7	123.5	94.3
Havirov	117.1	98.3	81.9	105.5	73.9	45.3
Budapest	97.4	86.4	73.6	185.2	173.3	157.7
Barcelona	5.7	5.3	4.8	9.5	9.3	9.0
Madrid	1.7	1.6	1.4	5.7	5.1	4.8
Valencia	3.7	3.3	3.0	8.1	7.8	7.4
Antwerp	180.1	159.9	136.1	142.6	120.6	91.7
Brussels	178.0	157.9	133.8	140.1	118.3	88.5
SintAmandsberg	176.8	156.9	133.2	138.1	116.7	87.7
Eindhoven	116.2	108.9	101.6	97.4	90.5	81.5
Groningen	130.4	122.7	114.2	96.3	89.1	80.7

Fig. 7. Average values and standard deviations of heating demand in three 30-year periods, each considering 13 future climate scenarios with five GCMs and three RCPs.

4.1. Model verification

The numerical model developed in IDA ICE is verified against the TABULA datasets (for heating) and EU report on STRATEGO [99] (for cooling) using the TMY weather data from the IDA ICE weather data library for one year. The triangles in Fig. 5 represent the reference values, whereas the circles represent the annual average heating/cooling demand as simulated by IDA ICE. Some of the TABULA heating demand values are not representative enough; for example, the heating demands for Gothenburg (in southwest Sweden) and Kiruna (in northern Sweden) are almost equal, whereas the demand for Kiruna should be higher than that of Gothenburg. For such a case, we rely on the IDA ICE simulation results, which are aligned with previous studies, for example, [39,26]. This also occurs for the cooling demand in Dublin, which is 0 according to the reference data; therefore, the cooling demand as calculated by IDA ICE for the TMY is used as the reference. For the heating demand, although two of the cities in Sweden have been previously discussed, the differences between the basic model and TABULA for Dipkarpaz, Nicosia, and Salzburg are 24%, 20%, and 23%, respectively, whereas IDA ICE did not predict such higher heating demands

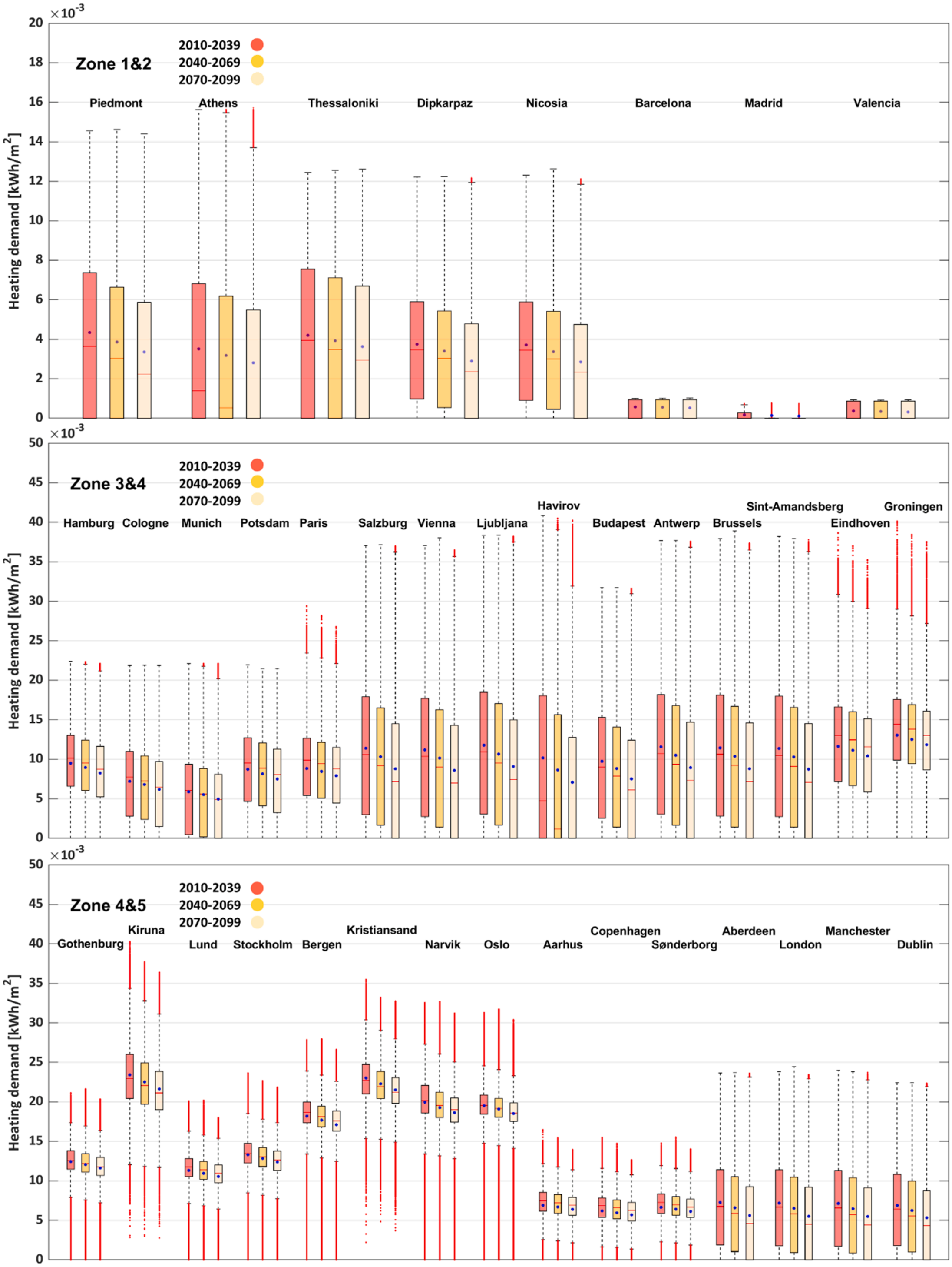


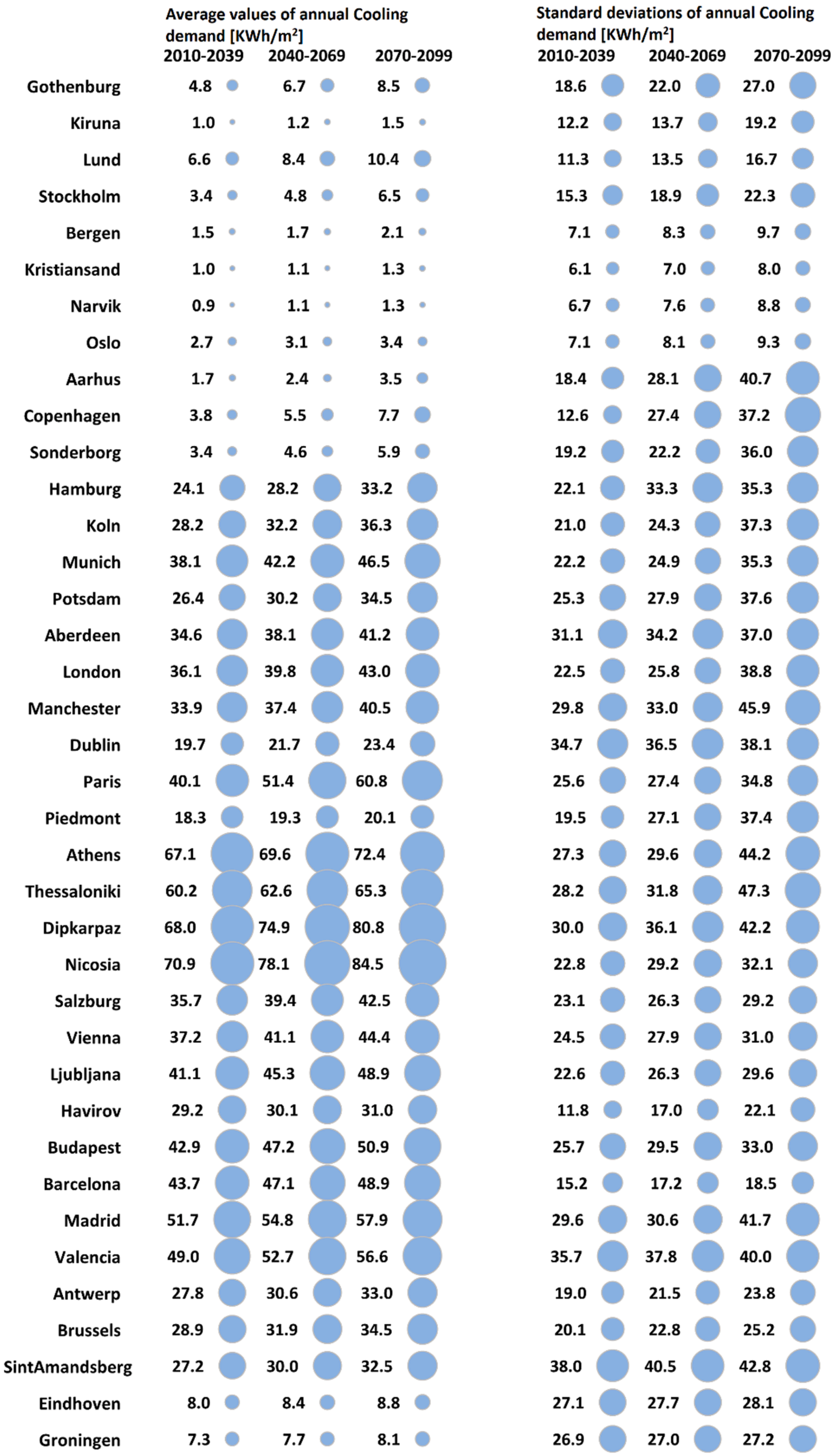
Fig. 8. Nonparametric distribution of the heating demand of buildings during the cold season over five European climate zones.

relative to TABULA. For the rest of the cities, the differences vary from 1% to 10%, for example, Athens (3%), Vienna (8%), and Valencia (1%). For the cooling demand, the difference between the basic model and reference for most of the cities varies from 1% to 9%, except for Gothenburg (17%), Athens (13%), Thessaloniki (14%), Dipkarpaz (23%), Nicosia (22%), Salzburg (21%), Vienna (14%), and Barcelona (16%), for which IDA ICE predicts higher cooling demands than the reference.

4.2. Future weather conditions

The temperature distribution for the future climate scenarios is shown for 38 European cities using boxplots in Fig. 6, with each including cities from two European climate zones. The average values are denoted by dark blue dots. The boxplots combine all five GCMs and three RCPs for each 30-year period, with hourly temporal resolution. In other words, each boxplot represents 3,416,400 temperature data points (13 climate scenarios × 30 years × 8760 h). This is done to consider all of the possible conditions in the assessment, knowing that all of the climate models are verified, and that none can be considered the best (as is thoroughly discussed in [28;26]).

According to the figures, the outdoor temperature will increase everywhere, which naturally implies an increase in the average and



	Average values of annual Cooling demand [KWh/m^2]			Standard deviations of annual Cooling demand [KWh/m^2]		
	2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
Gothenburg	4.8	6.7	8.5	18.6	22.0	27.0
Kiruna	1.0	1.2	1.5	12.2	13.7	19.2
Lund	6.6	8.4	10.4	11.3	13.5	16.7
Stockholm	3.4	4.8	6.5	15.3	18.9	22.3
Bergen	1.5	1.7	2.1	7.1	8.3	9.7
Kristiansand	1.0	1.1	1.3	6.1	7.0	8.0
Narvik	0.9	1.1	1.3	6.7	7.6	8.8
Oslo	2.7	3.1	3.4	7.1	8.1	9.3
Aarhus	1.7	2.4	3.5	18.4	28.1	40.7
Copenhagen	3.8	5.5	7.7	12.6	27.4	37.2
Sonderborg	3.4	4.6	5.9	19.2	22.2	36.0
Hamburg	24.1	28.2	33.2	22.1	33.3	35.3
Koln	28.2	32.2	36.3	21.0	24.3	37.3
Munich	38.1	42.2	46.5	22.2	24.9	35.3
Potsdam	26.4	30.2	34.5	25.3	27.9	37.6
Aberdeen	34.6	38.1	41.2	31.1	34.2	37.0
London	36.1	39.8	43.0	22.5	25.8	38.8
Manchester	33.9	37.4	40.5	29.8	33.0	45.9
Dublin	19.7	21.7	23.4	34.7	36.5	38.1
Paris	40.1	51.4	60.8	25.6	27.4	34.8
Piedmont	18.3	19.3	20.1	19.5	27.1	37.4
Athens	67.1	69.6	72.4	27.3	29.6	44.2
Thessaloniki	60.2	62.6	65.3	28.2	31.8	47.3
Dipkarpaz	68.0	74.9	80.8	30.0	36.1	42.2
Nicosia	70.9	78.1	84.5	22.8	29.2	32.1
Salzburg	35.7	39.4	42.5	23.1	26.3	29.2
Vienna	37.2	41.1	44.4	24.5	27.9	31.0
Ljubljana	41.1	45.3	48.9	22.6	26.3	29.6
Havirov	29.2	30.1	31.0	11.8	17.0	22.1
Budapest	42.9	47.2	50.9	25.7	29.5	33.0
Barcelona	43.7	47.1	48.9	15.2	17.2	18.5
Madrid	51.7	54.8	57.9	29.6	30.6	41.7
Valencia	49.0	52.7	56.6	35.7	37.8	40.0
Antwerp	27.8	30.6	33.0	19.0	21.5	23.8
Brussels	28.9	31.9	34.5	20.1	22.8	25.2
SintAmandsberg	27.2	30.0	32.5	38.0	40.5	42.8
Eindhoven	8.0	8.4	8.8	27.1	27.7	28.1
Groningen	7.3	7.7	8.1	26.9	27.0	27.2

Fig. 9. Average values and standard deviations of cooling demand in three 30-year periods, each considering 13 future climate scenarios with five GCMs and three RCPs.

extreme temperatures. For example, the probability of reaching above 35 °C will increase in many European cities, whereas in several others it exceeds 40 °C, such as in Athens. The highest average temperatures are in Dipkarpaz (Cyprus) and Madrid (Spain); however, the annual variations in these two cities are smaller than those in other cities. In cold cities such as Kiruna (Sweden) and Narvik (Norway), the range of extreme cold temperatures will decrease, with less-extreme low temperatures. As the outdoor temperature increases, it can be preliminarily

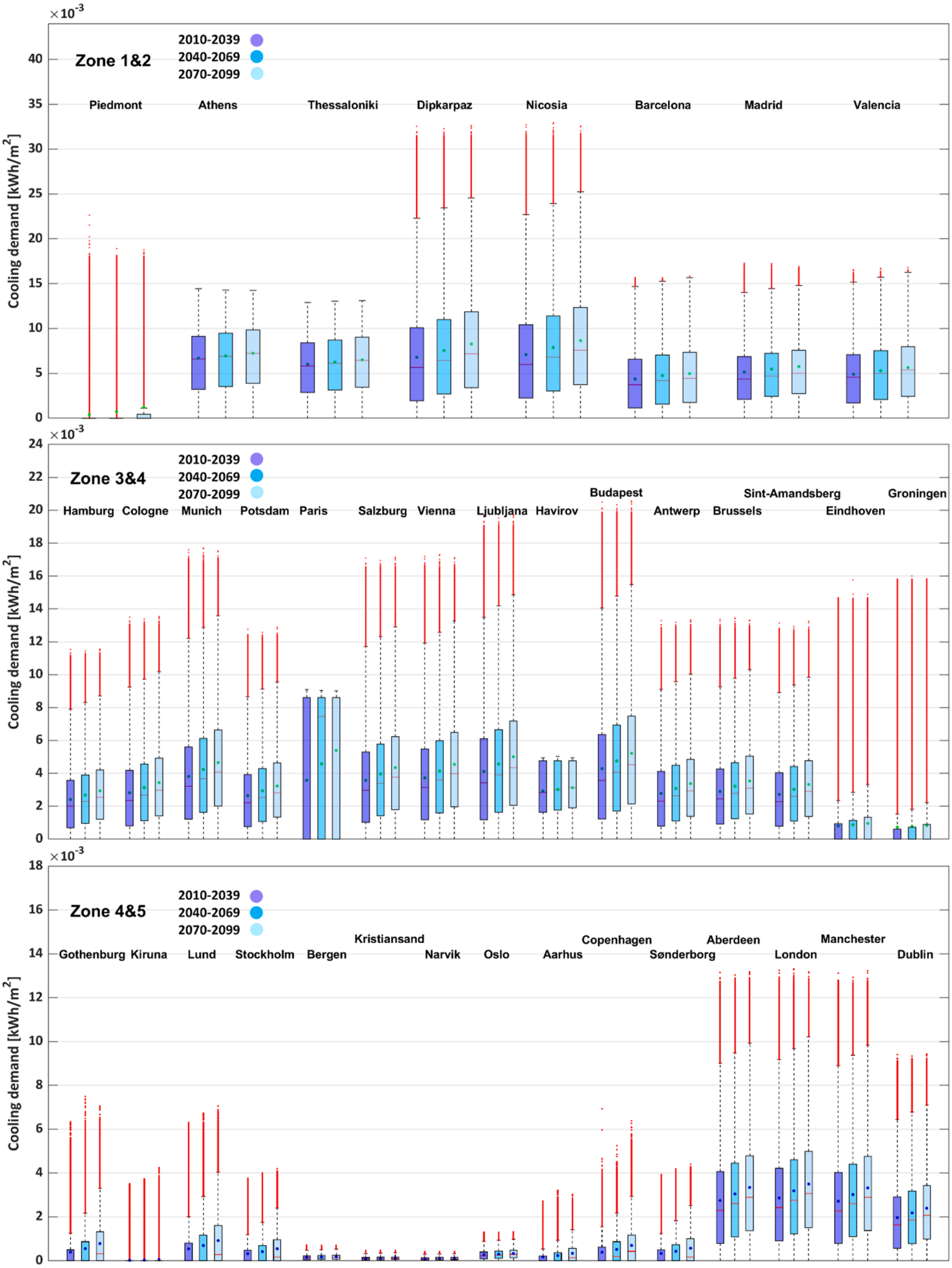


Fig. 10. Nonparametric distribution of the cooling demand of buildings during the warm season over five European climate zones.

inferred that on average, the heating demand in the future will decrease and the cooling demand will increase. However, understanding the actual impacts of climate change requires a more detailed analysis, especially concerning extreme weather events and thermal comfort, as discussed below.

4.3. Future heating demand

The climate change-induced variations in the energy demands of buildings, including heating and cooling demands, are investigated by simulating the hourly energy demands of buildings for the three 30-year periods, considering 13 climate scenarios. The assessment results for the heating demand are presented in this section based on calculating the average and standard deviations over the 30-year period, and by plotting the hourly energy demand values as boxplots. Fig. 7 provides a concise overview of the average and standard deviation of the heating demand values for three time periods. It is evident that the heating demand decreases from one period to the next. A more detailed overview is presented in Fig. 8, where the heating demand values in winter (December, January, and February) are plotted for different climate

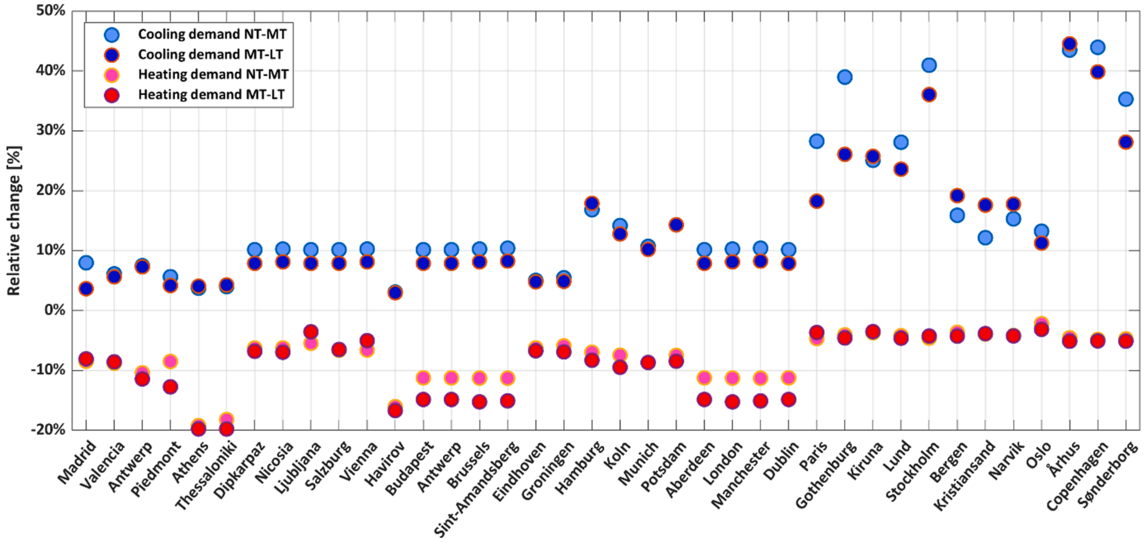


Fig. 11. Percentage of the relative change of average heating and cooling demand between NT-MT and MT-LT.

zones over the three 30-year periods. According to the boxplots in Fig. 8, for most of the cities, the upper whiskers and interquartile ranges exhibit a decreasing trend over time. For cities in zones 1 and 2 (warmer cities with a larger cooling demand during summer), the average heating demand decreases between NT and MT and varies between 5.4% and 19.2% (e.g., 19.2% in Athens and 6.2% in Nicosia); it varies between 6% and 19.7% for MT and LT (e.g., 19.7% in Athens and 6.9% in Nicosia).

The reduction in average heating demand between NT and MT in zones 3 and 4 countries varies between 4.6% and 16%, and for MT and LT, between 3.6% and 16%. Three Belgian cities (Antwerp, Brussels, and Sint-Amandsberg) have the most considerable reduction between each time period: 11%–12% between NT and MT, and 14%–15% between MT and LT. There are other cities with a similar trend, such as Havirov in zone 3 (with a 16% decrease in the inter-period decrease in heating demand) and Aberdeen, London, Manchester, and Dublin in zone 4. Among them, the three cities in the United Kingdom have 11% less heating demand in MT compared to NT, and 14%–15% less in LT than in MT. A similar trend can be found in Fig. 8 that the upper quartile of the heating demand has a decreasing trend. The relative decreases in the heating demand are smaller than those in the results from statistically downscaled (CCWorldWeatherGen) weather data (e.g., Aberdeen, 31% in 2050, and 45% in 2080 [58])

The heating demands in the Nordic countries (zone 5) have the smallest decreases between NT and MT, ranging from 2.7% to 4.8%. For example, the decrease between Gothenburg NT and MT is 4% and 4.5% between MT and LT, which are smaller than the values in the results from statically downscaled weather data (e.g., Gothenburg, 24% in 2050, and 36% in 2080 [58]). Similar results can also be seen for the heating demands during the cold season in zones 4 and 5. All of the cities show a downward trend in the heating demand over time, including upper whiskers and outliers. This means that there will be less extreme cold occasions with very high heating demands; however, the decrease is not very steady, implying looser heating measures for buildings in this zone. As shown in Fig. 8, there will still be considerable extreme cold conditions in the future. This is also visible in Fig. 7, where the standard deviation of heating demand varies little between time periods, i.e., between 2% and 29% between the first two periods, and between 2% and 38% between the last two periods (smaller variations for colder cities). These results are different from those from previous studies based on using IPCC SRES scenarios (e.g., based on AR4, such as [39,116]). The relative decreases in the heating demand between the 30-year periods are larger for the older IPCC scenarios, for example, approximately 30% for the A2 scenario [38].

4.4. *Future cooling demand*

In this section, the impact of climate change on the cooling demands of buildings is investigated. A statistical assessment similar to that in the previous section is performed to analyze future conditions, considering different temporal scales. According to the average and standard deviation of the cooling demands shown in Fig. 9, the demand will increase over time in all cities, in both their averages and variations. The seasonal cooling demands during summer (June, July, and August) in the five climate zones over three 30-year periods are plotted in Fig. 10. It can be seen that the interquartile ranges, as well as the upper whiskers and outliers, have an increasing trend. For cities in zones 1 and 2, the increase in the cooling demand between NT and MT is 3.7%–10.5%, and that between MT and LT is 3.6%–8%. For example, the rise between NT and MT in Athens is 3.7%, and that between MT and LT is 4%. For Nicosia, the value is 6.2% between NT and MT, and 6.9% between MT and LT. Nicosia shows an apparent increase in the upper quartile between NT and MT.

For most of the cities in zones 3 and 4, the average cooling demands increase 3%–28.2% between NT and MT, and by 2.9%–18.2% between MT and LT. The relative increase in the cooling demand is considerably higher than the relative decrease in the heating demand. For example, the average cooling demand in Paris increases by 28% during MT and by over 18.2% during LT (in comparison to the previous periods). These values beat the relative reduction in heating, i.e., 4.6% and 3.6% for similar periods, respectively.

Cities in zones 4 and 5 have colder climates with much smaller cooling demands, as shown in Fig. 9. With climate change, the relative variations in the cooling demands are considerable in these cities, and the average cooling demand varies the most. For example, in three Swedish cities of Gothenburg, Kiruna, and Stockholm, the increase in the average cooling demands between NT and MT are between 25% and 40%, and between MT and LT are between 23% and 36%. Making the same comparison for three cities in Denmark (Copenhagen, Aarhus, and Sonderborg), the cooling demand increases between NT and MT are 35%–44%, and those between MT and LT is 28%–45%.

In Nordic countries, which are heating-dominated countries with colder climates, the increase in the cooling demand is far more significant than the decrease in the heating demand. More than average values, the increase in the standard deviation of the cooling demand (NT and MT 12%–117%; MT and LT 13%–44% - see Fig. 9) is much greater than that of the heating demand (NT and MT 1.1%–3.4%; MT and LT 1.7%–3.8% - see Fig. 7). The standard deviation of the cooling demand

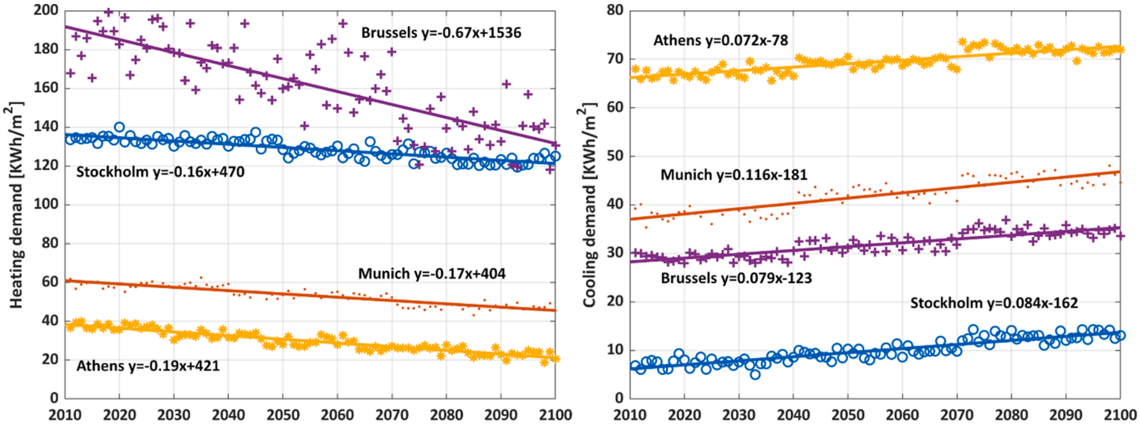
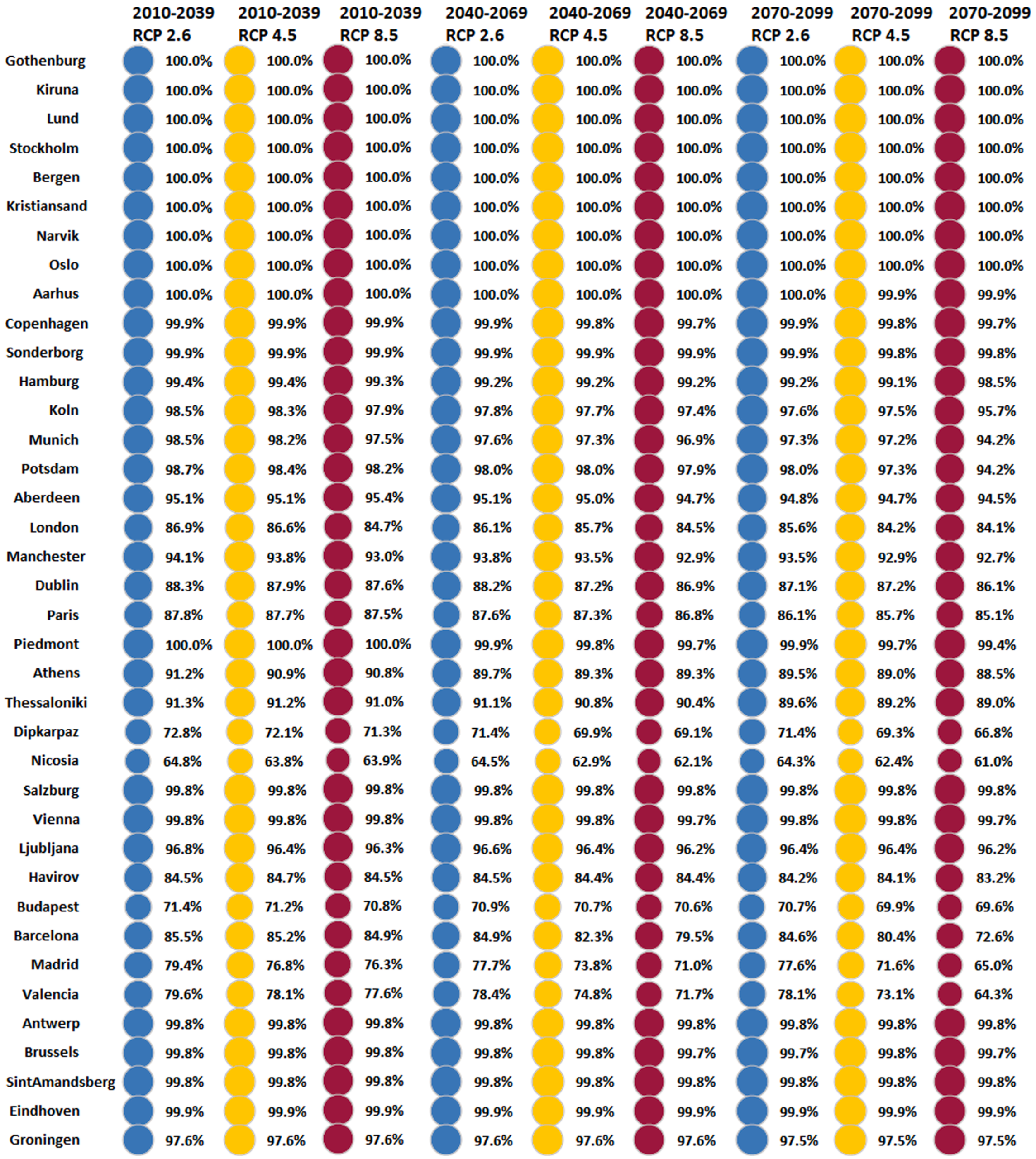


Fig. 12. Regression analysis of average heating demand and cooling demand.



	2010-2039 RCP 2.6	2010-2039 RCP 4.5	2010-2039 RCP 8.5	2040-2069 RCP 2.6	2040-2069 RCP 4.5	2040-2069 RCP 8.5	2070-2099 RCP 2.6	2070-2099 RCP 4.5	2070-2099 RCP 8.5
Gothenburg	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Kiruna	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Lund	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Stockholm	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Bergen	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Kristiansand	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Narvik	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Oslo	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Aarhus	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%
Copenhagen	99.9%	99.9%	99.9%	99.9%	99.8%	99.7%	99.9%	99.8%	99.7%
Sonderborg	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.8%	99.8%
Hamburg	99.4%	99.4%	99.3%	99.2%	99.2%	99.2%	99.2%	99.1%	98.5%
Koln	98.5%	98.3%	97.9%	97.8%	97.7%	97.4%	97.6%	97.5%	95.7%
Munich	98.5%	98.2%	97.5%	97.6%	97.3%	96.9%	97.3%	97.2%	94.2%
Potsdam	98.7%	98.4%	98.2%	98.0%	98.0%	97.9%	98.0%	97.3%	94.2%
Aberdeen	95.1%	95.1%	95.4%	95.1%	95.0%	94.7%	94.8%	94.7%	94.5%
London	86.9%	86.6%	84.7%	86.1%	85.7%	84.5%	85.6%	84.2%	84.1%
Manchester	94.1%	93.8%	93.0%	93.8%	93.5%	92.9%	93.5%	92.9%	92.7%
Dublin	88.3%	87.9%	87.6%	88.2%	87.2%	86.9%	87.1%	87.2%	86.1%
Paris	87.8%	87.7%	87.5%	87.6%	87.3%	86.8%	86.1%	85.7%	85.1%
Piedmont	100.0%	100.0%	100.0%	99.9%	99.8%	99.7%	99.9%	99.7%	99.4%
Athens	91.2%	90.9%	90.8%	89.7%	89.3%	89.3%	89.5%	89.0%	88.5%
Thessaloniki	91.3%	91.2%	91.0%	91.1%	90.8%	90.4%	89.6%	89.2%	89.0%
Dipkarpaz	72.8%	72.1%	71.3%	71.4%	69.9%	69.1%	71.4%	69.3%	66.8%
Nicosia	64.8%	63.8%	63.9%	64.5%	62.9%	62.1%	64.3%	62.4%	61.0%
Salzburg	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%
Vienna	99.8%	99.8%	99.8%	99.8%	99.8%	99.7%	99.8%	99.8%	99.7%
Ljubljana	96.8%	96.4%	96.3%	96.6%	96.4%	96.2%	96.4%	96.4%	96.2%
Havirov	84.5%	84.7%	84.5%	84.5%	84.4%	84.4%	84.2%	84.1%	83.2%
Budapest	71.4%	71.2%	70.8%	70.9%	70.7%	70.6%	70.7%	69.9%	69.6%
Barcelona	85.5%	85.2%	84.9%	84.9%	82.3%	79.5%	84.6%	80.4%	72.6%
Madrid	79.4%	76.8%	76.3%	77.7%	73.8%	71.0%	77.6%	71.6%	65.0%
Valencia	79.6%	78.1%	77.6%	78.4%	74.8%	71.7%	78.1%	73.1%	64.3%
Antwerp	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%
Brussels	99.8%	99.8%	99.8%	99.8%	99.8%	99.7%	99.7%	99.8%	99.7%
SintAmandsberg	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%	99.8%
Eindhoven	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%
Groningen	97.6%	97.6%	97.6%	97.6%	97.6%	97.6%	97.5%	97.5%	97.5%

Fig. 13. Percentage of the comfort hours in the representative buildings of 38 European cities for three 30-year periods considering three different RCPs.

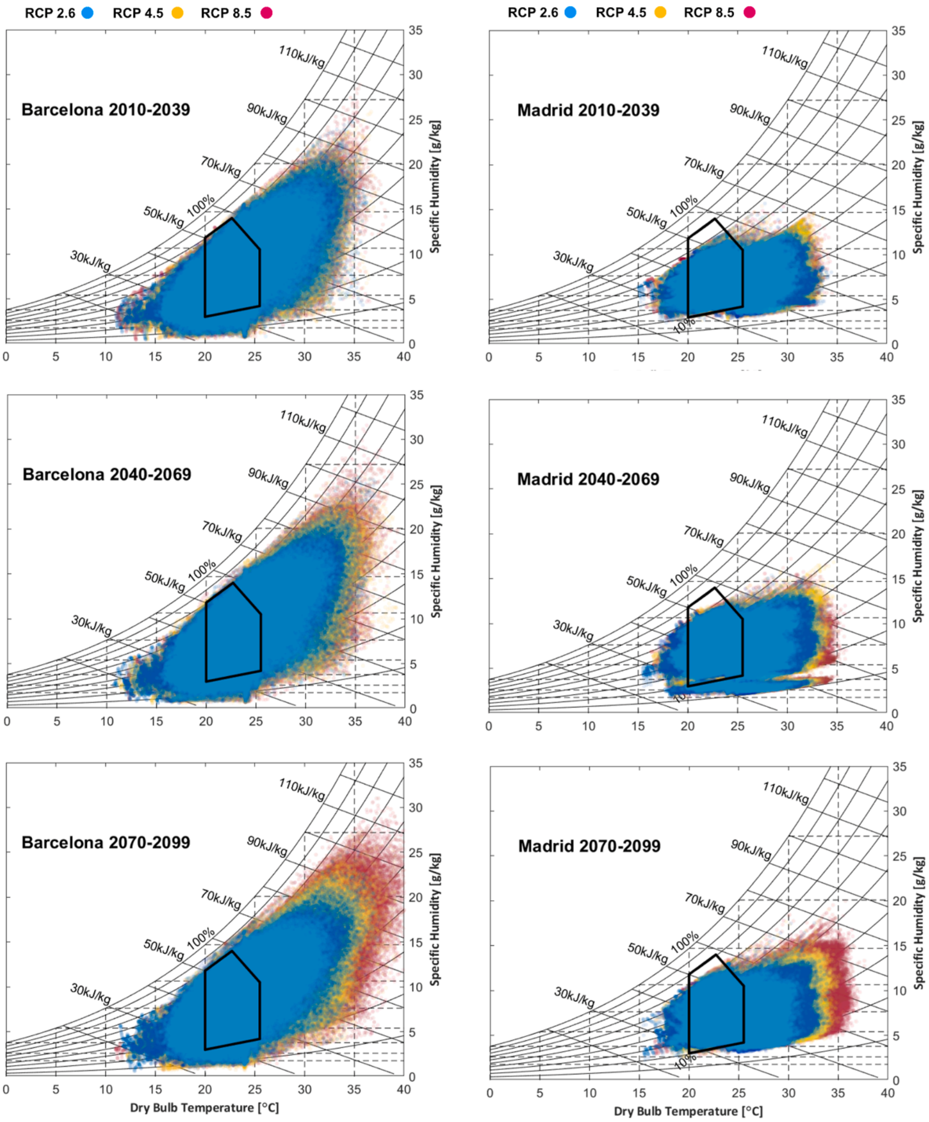


Fig. 14. Indoor condition distribution for Barcelona and Madrid (2010–2099).

significantly increases during the last period, indicating that the frequency and intensity of heatwaves or extreme warm hours will considerably increase by the end of the century. More than the increase in the average cooling demand, its distribution becomes wider with larger upper quartiles, whiskers, and outliers, as shown in Fig. 10, indicating the need for setting proper strategies for cooling buildings during warm periods in the future, even in the colder climate zones of Europe (where most of the residential buildings do not have any cooling system installed).

4.5. Overall changes in the heating and cooling demands

It is interesting to assess the overall changes owing to climate change in the heating and cooling demands in the considered cities, considering both the 30-year period and continuous (annual) trends. Fig. 11 summarizes the relative changes in the heating and cooling demands between periods. For example, “Cooling demand NT-MT” is calculated as the percentage of changes in the cooling demand between two periods, where the earlier period is the reference. According to Fig. 11, the largest impact of climate change on increasing the cooling demand occurs in northern Europe; however, it is important to consider that this cooling demand will remain much smaller than those of cities in warmer climate zones. For example, Aarhus and Copenhagen have the most apparent percentage increases. The relative reductions in heating demands are more evident between MT-LT for cities in zones 3 and 4 (e.g., Antwerp, London, and Manchester). For most of the Nordic cities (Zone 5), the relative reductions in the heating demands are almost equal between NT-MT and MT-LT.

The average heating and cooling demands are calculated for every year from to 2010–2099. To assess the trend in demand variations owing to climate change, a regression analysis is performed for different cities. Table A.2 (Appendix A) shows the regression equation used for all of the cities, along with the determination coefficient (R^2). The regression analysis shows the trends and variations in changes by time for heating and cooling. Most cities have similar trends; however, in some cities, the heating demand decreases more quickly (along with the increase in cooling demand), as discussed below with reference to Fig. 12. For all of the cities, the regression coefficient (R^2) is above 0.7. for cooling and is greater than R^2 value for heating, indicating a better regression fit for the cooling demand than for the heating demand.

Four cities from different climate regions (Stockholm, Athens, Munich, and Brussels) are selected to assess the average annual heating demands during 2010–2099 using regression analysis, as shown in Fig. 12 (left). The rates of decline in the heating demands in the cities are different. Among the four cities, the heating demand in Brussels has the steepest decline rate, with a more scattered distribution of annual values

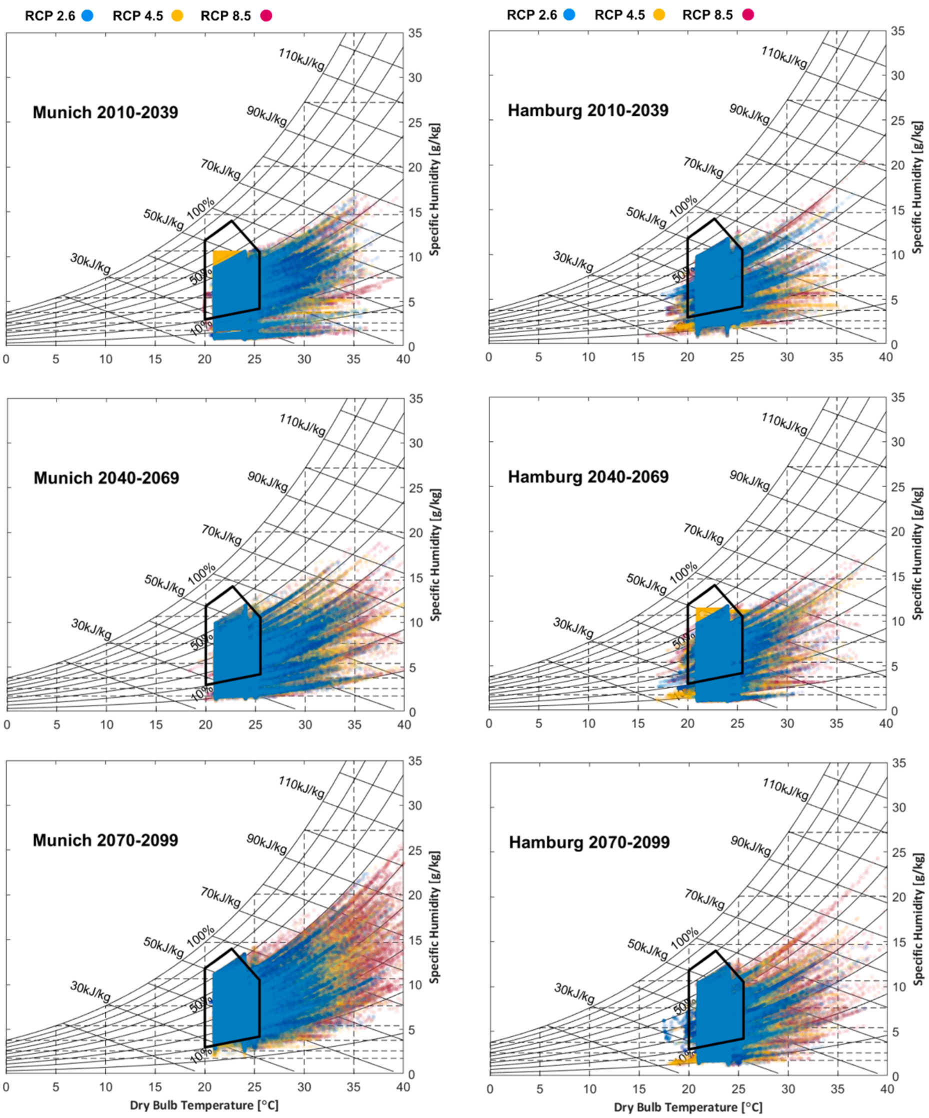


Fig. A.1. Indoor condition distribution for Munich and Hamburg (2010–2099).

around the trend line (the scattered points are more dispersed around the regression line). Munich and Stockholm show nearly identical decline rates, with a relatively narrow distribution around the trend line. Athens also shows a narrow distribution around the trend line, with a slightly steeper decline than Munich and Stockholm.

The cooling regression analysis for the same cities is shown in Fig. 12 (right). Apparently, the cooling demand rises for all of them. Among the four cities, Munich shows the most apparent upward trend. Munich also has the largest variations around the trend line, followed by Stockholm, Brussels, and Athens. Compared with the heating demand, the variations around the trend line are less scattered, demonstrating the (semi-)steady trend of the increase in cooling demand owing to climate change. As described in the previous section, the relative increases in the cooling demand over time are larger in cities from colder climate zones than those in warmer zones.

4.6. *Indoor thermal comfort*

This section presents the results of the indoor thermal comfort assessment for the considered buildings during the three time periods. To investigate how the different RCPs affect thermal comfort, the analysis is based on three groups of data: RCP 2.6, RCP 4.5, and RCP 8.5, with each using climate data from three GCMs: ICHEC-EC-EARTH, MOHC-HadGEM2-ES, and MPI-ESM-LR. Therefore, instead of 13 climate scenarios, nine climate scenarios are used for the assessment in this section. (Fig. A.1, Fig. A.2 and Fig. A.3 in Appendix A).

The percentage of comfort hours is shown in Fig. 13 for all of the cities, while eight cities from zones 1–4 are assessed using the psychrometric chart in Fig. 14 (Fig. A.1, Fig. A.2 and Fig. A.3 in Appendix A) (each figure covers one zone and two cities). According to Fig. 13, the heating-dominated cities in zone 5, such as the cities in Nordic countries, have better thermal comfort over all of the periods (over 99.9% of comfort hours). Traditionally, heating buildings has been a major concern in this zone, resulting in well-insulated buildings combined with efficient heating strategies. The overheating hours in Gothenburg and Copenhagen (see Fig. A.3 in Appendix A) are rare, with a very small increase over time (e.g., increase in LT) and RCP number (e.g., increasing for RCP 8.5).

In general, the percentage of comfort hours decreases as the RCP number increases and time passes. For example, in Barcelona and Madrid, as shown in Fig. 14, the numbers of overheating hours increase during LT, reaching 35% for Madrid and 27% for Barcelona. The increased discomfort hours caused by overheating indicate that the current cooling capacity cannot cope with the impacts of climate change.

The percentage of comfort hours for cities located in zone 3 is over

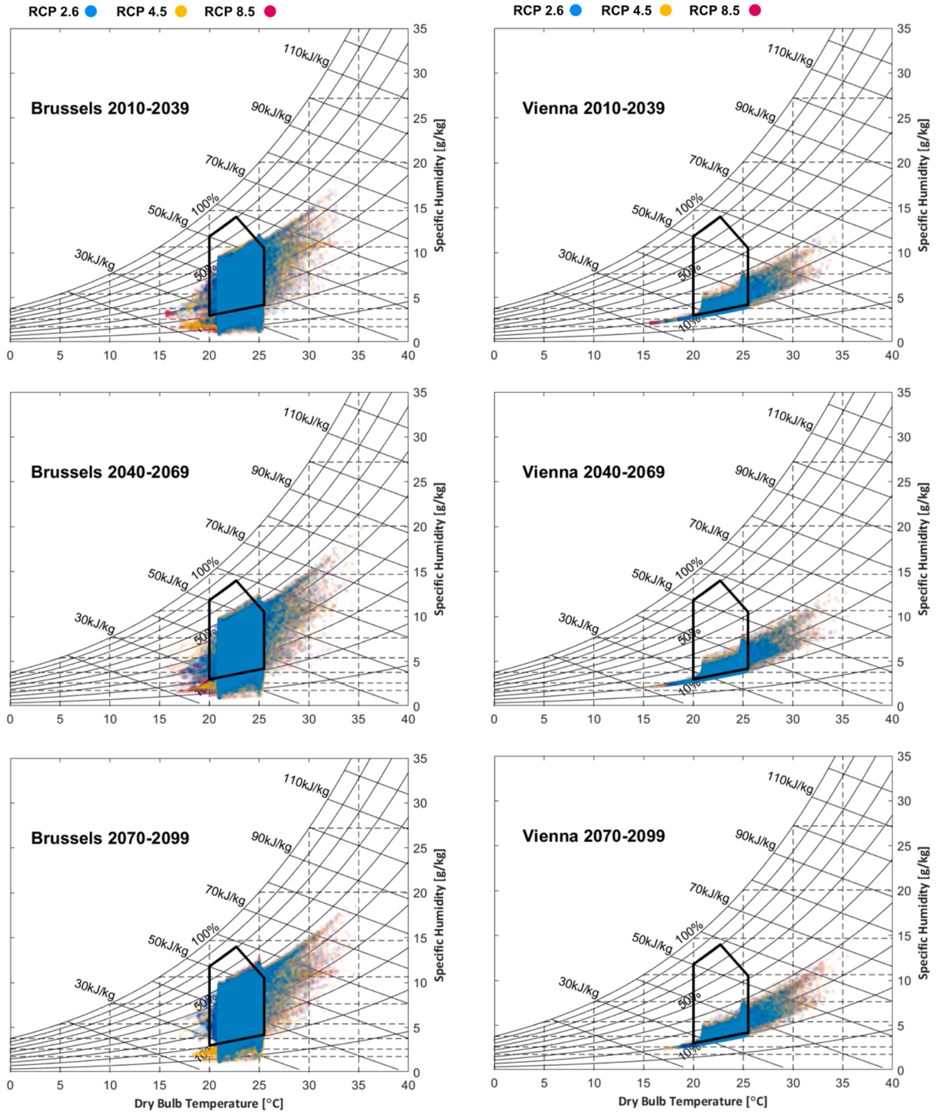


Fig. A.2. Indoor condition distribution for Brussels and Vienna (2010–2099).

86%, but the impacts of climate change are still visible. For example, in Germany (Fig. A.1 in Appendix A), the number of overheating hours increases with time; in Munich and Hamburg, the discomfort hours owing to overheating are 0.2%–0.4% in LT (although still very small).

For most cities in zone 4, the comfort hours are over 87%, which is second only to the zone 5 cities. Among other cities in zone 4, Brussels and Vienna (Fig. A.2 in Appendix A) have the best thermal comfort (over 99%), and overheating hours are rare and over time, for example, with increases in time and the number of RCPs.

5. Conclusions

During the past 30 years, significant efforts have been made to reduce the energy demands of buildings, including residential buildings. Such sustainable solutions will positively contribute to climate change mitigation by reducing energy demands. However, it is essential to account for the climate change adaptations of sustainable solutions; otherwise, they may result in less indoor comfort or higher energy demands in the future, and create a vicious cycle. To avoid this and develop proper adaptive solutions, it is necessary to properly assess the probable impacts of climate change, which requires investigating both the long-and short-term variations in future climate and considering multiple future climate scenarios and uncertainties.

This work provided an extensive impact assessment of climate change on the energy performances and thermal comfort of residential building stocks in 38 European cities belonging to five different climate zones in Europe. The study was based on the analysis of the energy demands of buildings, by comparing their heating and cooling demands and indoor thermal comfort considering different climate scenarios and geographic locations. The representative residential buildings in the cities were numerically modeled in IDA ICE according to TABULA and three other European projects, namely STRATEGO, ENTRANZE, and BPIE. A comprehensive set of future climate data sets was used in this study, considering three RCPs (RCP 2.6, RCP 4.5, and RCP 8.5) and five GCMs, resulting in 13 different future climate scenarios. Having the GCM data dynamically downscaled by RCA4 RCM with a fine temporal and spatial resolution over 2010–2099 created an ensemble of future weather data reflecting a wide range of long-and short-term variations in climate, including extreme climate events, at an hourly temporal resolution.

Assessments of 13 climate scenarios showed that extreme climate events may become larger and more frequent over all five climate zones, with significant potential impacts on the energy performances of buildings. As expected from a warmer climate, heating demands will decrease in the future, whereas cooling demands will increase; however, the variations differ based on the climate zone, especially considering

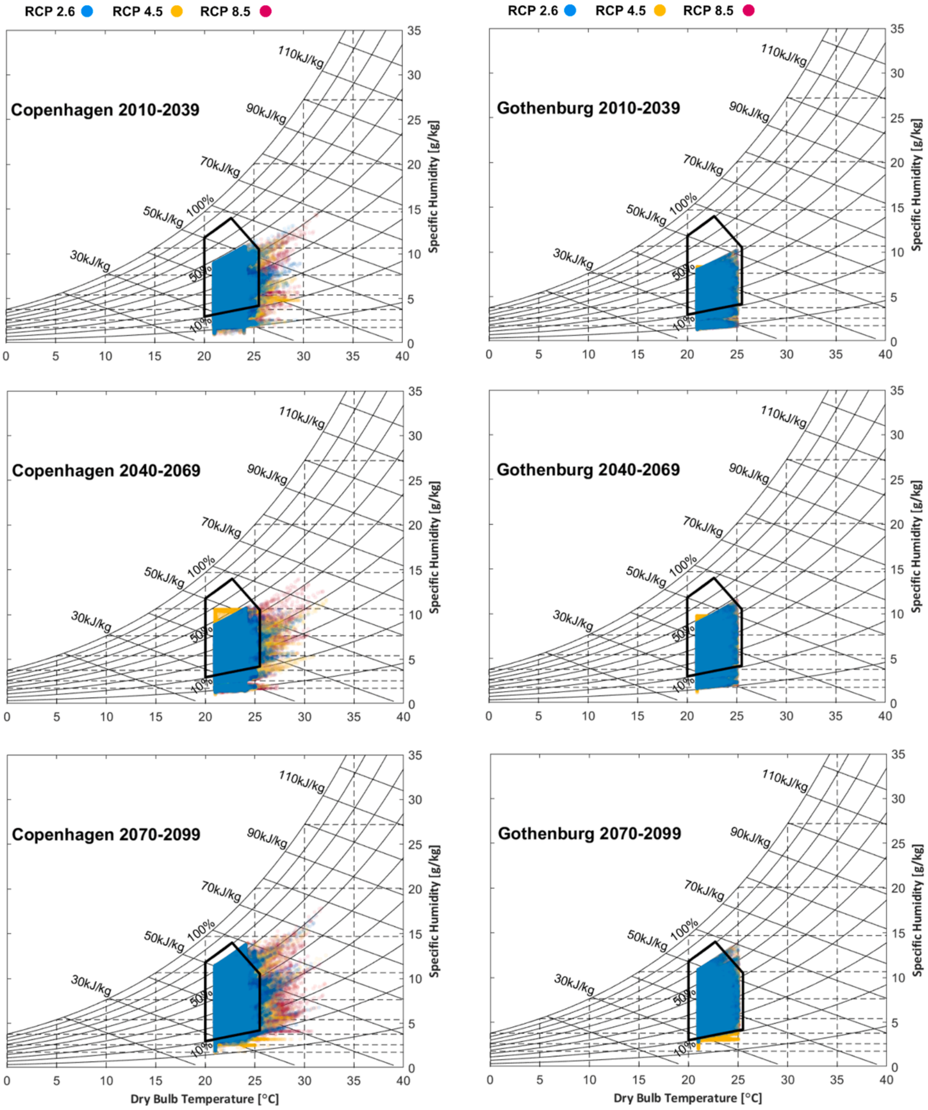


Fig. A.3. Indoor condition distribution for Copenhagen and Gothenburg (2010–2099).

Table A.1
The German residential building stock status.

Housing type	Building type	Erection period	number of buildings
Single Family House (SFH) (<= 2 apartments)	SFH I	until 1978	9,610,000
	SFH II	1979–1994	2,710,000
	SFH II	1995–2009	2,670,000
Multi Family House (MFH) (>=3 apartments)	MFH I	until 1978	2,340,000
	MFH II	1979–1994	440,000
	MFH III	1995–2009	270,000
Total			18,040,000

the relative changes in the cooling demand. For example, in zones 1 and 2, the average heating demands decrease between NT and MT by 5.4%–19.2%, and between MT and LT by 6%–19.7%. Such decrements (respectively) are 6.5–16.0% and 5.0–16.6% for Zone 3, 4.6–11.3% and 3.6–15.2% for Zone 4, and 2.7–4.8% and 3.5–5.1% for Zone 5. Comparing the Swedish cities in Zone 5 with previous studies based on IPCC AR4 climate scenarios reveals that the decreases in the future heating demands for the IPCC AR5 scenarios (introducing RCPs) are smaller than those AR4. The increase in the average cooling demand owing to climate change also varies according to the climate zone. The increase between NT and MT in zones 1 and 2 varies by 3.5%–3.5% and that between MT and LT by 3.6%–8%. These increments are (respectively) 3–10.2% and 2.9–8% for Zone 3, 5–28% and 4.7–18.2% for zone 4, and 12–44% and 11.2–45% for Zone 5. The relative increases in the cooling demands between each period are much higher than the relative decreases in the heating demands for colder climate zones, such as Zone 5. Such extreme short-term loads can considerably challenge an urban energy system, as covering them will require an increase in the energy generation capacity of traditional energy systems and those with small flexibility. It can be seen that the standard deviation of the cooling demand significantly increases during the last 30 years of the range, meaning that the frequency and intensity of heatwaves or extreme warm hours will considerably increase by the end of the century. Accordingly, it is necessary to set proper strategies for cooling buildings during warm periods in the future, even in colder climate zones of Europe. This can introduce new challenges to the building and energy market/industry, as the majority of residential buildings in Europe do not have any cooling system installed. Although heating demand will decrease in the future, it will be still high and dominant in many climate zones, even with considerable extreme cold conditions.

Considering the indoor thermal comfort, most cities in zones 1 and 2 (cooling-dominated cities) are vulnerable to climate change, owing to their warmer summers and more frequent overheating. For example, in

Table A.2
Regression analysis of European cities.

Country	City	Heating regression	Cooling regression	R2(Heating)	R2(Cooling)
Austria	Salzburg	y = −0.15x+429.31	y = 0.047x-56.74	0.76	0.84
	Vienna	y = −0.18x+ 480.92	y = 0.045x-50.55	0.75	0.81
Belgium	Antwerp	y = −0.39x+ 916.36	y = 0.029x-27.54	0.94	0.84
	Brussels	y = −0.67x+ 1536.50	y = 0.079x-123	0.73	0.73
	Sint-Amandsberg	y = −0.40x+ 93	y = 0.030x-31.92	0.92	0.88
Cyprus	Dipkarpaz	y = −0.14x+ 317.69	y = 0.107x-141.60	0.76	0.77
	Nicosia	y = −0.19x+ 427.12	y = 0.119x-162.51	0.77	0.73
Czech	Havířov	y = −0.17x+ 419.71	y = 0.023x-19.46	0.70	0.76
Denmark	Århus	y = −0.20x+ 453.13	y = 0.027x-53.35	0.79	0.96
	Copenhagen	y = −0.21x+ 481.78	y = 0.027x-47.38	0.79	0.92
	Sønderborg	y = −0.20x+ 464.26	y = 0.026x-46.35	0.78	0.88
France	Paris	y = −0.14x+ 352.83	y = 0.318x-602.51	0.71	0.89
Germany	Hamburg	y = −0.14x+ 361.00	y = 0.048x-75.23	0.75	0.75
	Cologne	y = −0.162x+ 376.03	y = 0.045x-64.48	0.79	0.73
	Munich	y = −0.17x+ 404.09	y = 0.116x-181	0.81	0.76
	Potsdam	y = −0.16x+ 398.64	y = 0.050x-75.63	0.80	0.79
Greece	Athens	y = −0.19*x+ 421.39	y = 0.072x-78	0.86	0.77
	Thessaloniki	y = −0.20x+ 456.52	y = 0.049x-40.37	0.81	0.75
Hungary	Budapest	y = −0.19x+ 458.62	y = 0.044x-42.40	0.70	0.74
Ireland	Dublin	y = −0.23x+ 551.58	y = 0.051x-80.70	0.74	0.87
Italy	Piedmont	y = −0.18x+ 411.86	y = 0.026x-40.61	0.72	0.79
Netherlands	Eindhoven	y = −0.14x+ 374.18	y = 0.024x-39.63	0.71	0.89
	Groningen	y = −0.14x+ 372.32	y = 0.021x-35.60	0.73	0.79
Slovenia	Ljubljana	y = −0.21x+ 539.79	y = 0.053x-62.08	0.76	0.85
Spain	Barcelona	y = −0.12x+ 261.39	y = 0.048x-53.70	0.71	0.88
	Madrid	y = −0.13x+ 284.01	y = 0.043x-33.98	0.74	0.86
	Valencia	y = −0.12x+ 261.59	y = 0.046x-40.36	0.88	0.89
Sweden	Gothenburg	y = −0.207x+ 500.54	y = 0.063*x-125	0.80	0.79
	Kiruna	y = −0.21x+ 596.07	y = 0.038x-77.75	0.75	0.76
	Lund	y = −0.19x+ 468.21	y = 0.044x-84.13	0.76	0.83
	Stockholm	y = −0.16x+ 470.00	y = 0.084x-162	0.73	0.80
United Kingdom	Aberdeen	y = −0.20x+ 495.10	y = 0.05x-69.27	0.76	0.74
	London	y = −0.21x+ 506.20	y = 0.049x-60.26	0.72	0.75
	Manchester	y = −0.20x+ 499.15	y = 0.048x-59.86	0.73	0.82
Norway	Bergen	y = −0.23x+ 612.60	y = 0.026x-53.81	0.79	0.74
	Kristiansand	y = −0.21x+ 590.51	y = 0.037x-74.52	0.79	0.78
	Narvik	y = −0.22x+ 627.24	y = 0.035x-71.03	0.82	0.80
	Oslo	y = −0.20x+ 562.96	y = 0.034x-67.32	0.76	0.79

Valencia, Nicosia, and Dipkarpaz, overheating hours account for 20%–30% of the summertime. This points to a greater need for cooling buildings in the future. Overheating also occurs in zone 3, including cities such as Budapest and Havirov, with overheating hours in 16%–29% of the summertime. In most of the cities in zones 4 and 5, the impacts of climate change on the indoor thermal comfort are negligible, with the best indoor thermal comfort values across Europe over the entire time period. Although climate change influences the building energy demands in zones 4 and 5, the performances of these buildings are less affected by climate change than those in other zones. For the cities showing overheating, the increased discomfort hours caused by the overheating indicate that the current cooling capacities cannot cope with the impacts of climate change. For air-conditioned buildings, achieving better thermal comfort requires a higher cooling capacity during the summer. This leads to larger loads on the electricity and power networks in such cities, as the cooling and air-conditioning systems mainly rely on electricity.

This work provides further evidence on the importance of considering both long- and short-term variations of climate, including extreme events, when assessing future energy solutions and the energy performances of building stocks. This study revealed that short-term extreme climate events lead to notable variations in energy demands and peak loads in different climate zones in Europe. This is critical when assessing the energy and climate resilience of buildings and urban areas. The availability of fine spatiotemporal resolution climate data is immensely helpful in assessing the plausible energy demands of buildings; however, it is important consider climate uncertainties, multiple scenarios, and extreme climate events. Such comprehensive impact assessments of climate change are essential for laying the groundwork for sustainable energy transitions in cities. Future work also needs to be conducted considering urban climate models, a wider range of building archetypes, finer spatial resolutions of building stocks, and socioeconomic parameters. Conducting such analyses (and their results and datasets) will enable decision-makers, engineers, and designers to account for future climate changes in their works from an early design stage.

CRediT authorship contribution statement

Yuchen Yang: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft. **Kavan Javanroodi:** Supervision, Writing - review & editing. **Vahid M. Nik:** Conceptualization, Supervision, Writing - review & editing, Funding acquisition, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Figs. A.1–A.3 and Tables A.1 and A.2.

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