Energy & Buildings 226 (2020) 110397

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Climate change impacts on trends and extremes in future heating and cooling demands over Europe

M.A.D. Larsen [a,*], S. Petrović [a], A.M. Radoszynski [a,b], R. McKenna [a,c], O. Balyk [a,d]

[a] Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs Lyngby, Denmark
[b] Ørsted, Nesa Allé 1, 2820 Gentofte, Denmark
[c] School of Engineering, University of Aberdeen, Aberdeen, UK
[d] MaREI, the SFI Research Centre for Energy, Climate and Marine, Environmental Research Institute, University College Cork, Cork, Ireland

ARTICLE INFO

Article history:
Received 25 March 2020
Revised 10 August 2020
Accepted 14 August 2020
Available online 18 August 2020

Keywords:
Heating
Cooling
Buildings
Climate Change
Energy System Analysis
Climate-Energy Nexus

ABSTRACT

The paper analyses effects of changes in temperatures on heating and cooling demands in Europe until 2050. Specifically, the study addresses changes in trends (10-year mean) and extremes (10-year min/-max). The analysis is based on two GHG emission climate scenarios (RCP2.6 and RCP4.5) and eight high-resolution regional climate models and results are provided as relative and absolute changes on grid and country scales. Population density is used as proxy for spatial distribution of demands.

Projected future temperatures are proportional with RCP scenario and distance into the future and the highest relative changes occur towards north-eastern Europe and for high-altitude areas. The temperature changes lead to general decreased heating demands and corresponding increased cooling demands. In general, higher spreads are seen between demand change ratios for individual models when addressing extremes as opposed to trends: The general 2010–2050 change ratios for heating between countries are 0.85–95 for model means and average 0.69 for the extreme analysis. For cooling, corresponding ratios are 1.25–1.5 for model means and average 2.76 for model maxima. For absolute demand changes, some countries are projected to experience significant changes e.g. exceeding a doubling in cooling demands. The results are suggested as a basis for energy system analyses.

1. Introduction

The building sector is regarded as a main contributor to the global energy consumption, and therefore also greenhouse gas emissions [1]. It currently accounts for 40% of the primary energy consumption in the US and EU [2] and 30% and 36% of energy-related CO_2 emissions globally [3] and for EU [4], respectively including electricity related losses. In a European context, residential buildings make up around 75% of the total European building floor area [5], in which around 60% of these energy demands and emissions are related to heating and cooling applications [6]. In western countries, heating, ventilation, and air conditioning systems (HVAC) [7] together make up 50–70% of the total residential energy use [8]. Whilst large differences between European member states are seen, exemplified by e.g. large shares of district heating in the Nordic region, around 90% of heat generation occurs in the building it supplies [9].

Approaches to decarbonise the building stock through energy efficiency and renewable energy have therefore been a main focus of research during the past decades [8], and hold significant potential for future GHG reductions [10-12]. Currently, energy efficiency research areas include among others: improved thermal insulation [13], implementations within materials such as phase change and energy storage [14] smart energy management and control [15,16] and market mechanisms such as managing consumption in relation to fluctuating prices [17]. Approaches to analyse the decarbonisation of the residential heating sector often take a national or international perspective due to the complex interaction effects, e.g. between electricity and heat sectors [18].

The heating and cooling demands in buildings depend on the indoor temperature, the outdoor temperature and the thermal characteristics of the building. Other factors could also be addressed, and these include e.g. snow cover [19], humidity, wind speed, cloud cover, etc. These factors are strongly affected by diverse underlying drivers such as occupancy and heating patterns, ventilation behavior, building aspect, window size, solar irradiation etc. but outside the scope of this study. At the regional/national levels, as often employed in large energy system models, the development of the heating and cooling demands depends on the construction and demolition rates, energy efficiency standards of newly built and renovated buildings and behavioural factors [20]. When analysing

* Corresponding author.
E-mail address: madla@dtu.dk (M.A.D. Larsen).

https://doi.org/10.1016/j.enbuild.2020.110397
0378-7788/

heat saving measures, the thermal characteristics of a buildings' envelope is the variable which can be varied the most, while the indoor temperature is typically varied in the narrow range of 18–22 °C as recommended by e.g. WHO [21-23]. Wider recommended indoor temperatures are however seen in the range of 19–28 °C as e.g. in the ASHRAE housing recommendations [24].

Other than the thermal characteristics of a certain building stock, the heating and cooling demands of buildings depend in particular on the outdoor temperatures, against which the indoor temperatures need to counterbalance. The past 100 years have shown a general increase in the mean annual global (outdoor) temperature of approximately 1 C° [25]. Future projections are often embodied in the use of the most recent IPCC (the Intergovernmental Panel of Climate Change) scenario, which for the most recent assessment report (no. 5) [25] where entitled RCP (representative concentration pathways) scenarios. These future scenarios predict an increase in the global mean temperature of further 1–4 C° (relative to 1986–2005) by 2100, depending on the scenario [25]. The regional variations in the projected warming are vast and are, among others, dependent on distance to larger bodies of water and altitude/topography as also seen for Europe, which is the focus area of this study. In conjunction with the general warming, studies show confidence that extreme temperature occurrences, i.e. droughts, heatwaves and related magnitudes, duration, spatial extent and frequencies, will increase [25-27]. These types of temperature extremes have the ability to enforce substantial implications for heat and cooling supply systems, which could need to be re-dimensioned in order to meet peak heating or cooling load demands during the year, season or day in question. Minimum and maximum temperatures, which are often used to depict temperature variations at shorter timescales such as sub-daily, are also projected to increase, although at spatially varying rates [28].

Future heating and cooling demands are often projected using correlations with economic and population forecasts whereas the climate is implicitly assumed constant or variability and extremes are not included [23]. In literature, the assessments of future heating and cooling demands have various forms such as in [29,30] employing cooling- and heating degree-days and there is a vast majority of studies at the local scale [31]. Other studies employ additional variables such as relative humidity [32] and radiation balance measures and wind [33]. The prevailing climate in Denmark results in a reduced heating demand of 7% for every degree (C°/K) increase in temperature [34] and another study showed that out of four factors influencing the heating demand in Stockholm, the choice of global climate model (acting as the signal of climate change) introduced the largest uncertainty (30%) followed by emission scenario (11%), choice of regional climate model (10%) and initial conditions (5%) [35]. At the same time, the building attributes have been shown to have a large effect on the impact of climate change on residential energy demands [7]. In summary, only a few studies have investigated the impact of climate change on heating and cooling demands on continental/decadal scales [30] but the effect of climate extremes, which impacts peak energy system demands, remains largely unexplored.

In this light, this study aims to analyse the effects of changes in temperatures trends and extremes on European heating and cooling demands from a national energy system point of view and can be used as an input to any energy systems model addressing heating and cooling demand changes. The contributions to literature of this study include: I) The calculation of heating and cooling demand changes based on changes in heating degree days (HDD) and cooling degree days (CDD) for the full ensemble of shared state-of-the-art climate models from the low-to-medium GHG emission scenario climate projections (RCP2.6 and RCP4.5 - eight models) over Europe in 12.5 km resolution. II) Applying population-based weighting of demand changes to account for not only climatological spatio-temporal changes but also account for the spatial distribution of demands, and: III) Derivation of changes in heating and cooling demands as general trends (decadal means) as well as extremes (decadal and seasonal min/max), both of which are derived as both the model ensemble mean and the ensemble min/max.

All results are made on the spatial scale of the climate models applied (12.5 km grids) and on country level across EU. The entire work is based on openly available data.

2. Methodology

2.1. Temperature data

The study utilizes the low- to medium climate change scenarios RCP2.6 and RCP4.5 [25] up until the year 2050 and the study area covers Europe. To accommodate this, the climate change signal and the implications for changes in future heating and cooling demands investigated here therefore employs the CORDEX database [36] which is the most recent effort of collecting output from regional climate models (RCM) from a wide range of contributing organisations and with continuous model additions. An RCM is defined as a computer model capable of simulating geophysical processes in the atmosphere and land surface where the geographical extent is a subset of the globe. The subset nature necessitates RCMs to have boundary conditions not just laterally (along the land-surface interface and towards the top of the atmosphere) but also at the horizontal edges/boundaries. For future projections in CORDEX, the RCMs are forced along the horizontal model domain boundaries by global climate models (GCMs). In this manner, RCMs and GCMs can be combined to form a simulation of e.g. future conditions as represented by RCP scenarios. Within the climate modelling, it is widely acknowledged that both the choice of RCM as well as GCM enforce a significant impact on resulting model output [37,38], and therefore multi model ensembles are generally used in impact studies for added robustness [39-41]. For this study, we employed every available RCM/GCM combination shared by the RCP2.6 and RCP4.5 scenarios available at the 12.5 km^2 resolution, which is the finest spatial resolution available for multi-model analyses. The ensemble comprised the eight model combinations listed in Table 1.

Prior to the heating and cooling demand change calculations, the variables of near surface air temperature, daily maximum near-surface air temperature and daily minimum near-surface air temperature were analysed to assess spatio-temporal patterns. In the methodology used here (see section 2.2), these variables are included to account for sub-daily patterns even when using daily data. In the RCM community, these variables appear as 'tas', 'tas_{max}' and 'tas_{min}' respectively, whereas we here use the terms T_{mean}, T_{max} and T_{min}. Temporally, the analysis was done by extracting 10-year running means from a historical reference period and until 2050 every fifth year (until 2050). In this paper, we present data from 2010 and 2050 (to some extent also 2030), representing, for the two former, present-day reference conditions and near-future conditions respectively based on 10-year periods (e.g. 2046–2055). The thresholds of 22 °C and 15.5 °C were used for T_{max} (days above) and T_{min} (days below) respectively as these are the thresholds used for the calculation of changes in cooling and heating demands as outlined in section 2.2 [33]. Further, to assess the spatial inter-model variability, the standard deviation between models was calculated for all three variables of T_{mean}, T_{max} and T_{min} and for both RCP scenarios (RCP2.6 and RCP4.5). This serves as a measure of robustness highlighting potential differences between different regions within the European domain. For T_{mean}, the standard deviations were calculated based on projected inter-model T_{mean} values

Table 1
The RCM and GCM models used in the study and the corresponding organisations.

No.	RCM model	Driving GCM model	Short name combined	Organisation
1	CCLM4	EC-EARTH	CCLM4_EC	Community Land Model (CLM) community
2	HIRHAM5	EC-EARTH	HIRHAM5_EC	Danish Meteorological Institute (DMI)
3	RACMO22	EC-EARTH	RACMO22_EC	Koninklijk Nederlands Meteorologisch Instituut (KNMI)
4	RACMO22	HADGEM2	RACMO22_HAD	Koninklijk Nederlands Meteorologisch Instituut (KNMI)
5	REMO2009	MPI-ESM-LR	REMO2009_MPI	Max Planck Institute (MPI)
6	RCA4	EC-EARTH	RCA4_EC	Swedish Meteorological and Hydrological Institute (SMHI)
7	RCA4	HADGEM2	RCA4_HAD	Swedish Meteorological and Hydrological Institute (SMHI)
8	RCA4	MPI-ESM-LR	RCA4_MPI	Swedish Meteorological and Hydrological Institute (SMHI)

from the entire model ensemble. For T_{max} and T_{min}, the standard deviations were calculated between models based on the numbers of days per year above or below the thresholds described above.

2.2. Heating and cooling degree days

In this analysis step, the RCM data were employed to calculate mean (RCP2.6) as well as extreme (RCP2.6 and RCP4.5) changes in future HDDs and CDDs over Europe from 2010 up until 2050. The starting point in the present analysis is that the future changes in heating and cooling demands are proportional to the future heating and cooling degree days (HDD and CDD, respectively). The future HDD and CDD are calculated for all grid cells (12.5 km resolution), stemming from the finest scale CORDEX RCM model outputs, covering Europe.

The HDDs and CDDs were calculated per cell using equations 1–2 and 3–4 respectively as obtained from [29]. Heating degree days are calculated during the cold period (Oct 1 to March 31 – 183 days in non-leap years) and cooling degree days in the warm period (Apr 1 to Sep 30 – 182 days). All variables (T_{mean}, T_{max} and T_{min}) are included in the calculation of degree days depending on the criterion temperature (Equation (1) and (3) below).

The HDD and CDD is calculated for every cell i and time step t based on the methodology presented in [29]:

$$HDD_{i,t} = \begin{cases} T_{b,h} - T_{M,i,t} \\ \frac{T_{b,h}-T_{N,i,t}}{2} - \frac{T_{X,i,t}-T_{b,h}}{4} \\ \frac{T_{b,h}-T_{Ni,t}}{4} \\ 0 \end{cases} \text{if} \begin{cases} T_{b,h} \geq T_{X,i,t} \\ T_{M,i,t} \leq T_{b,h} < T_{X,i,t} \\ T_{N,i,t} \leq T_{b,h} < T_{M,i,t} \\ T_{b,h} \leq T_{N,i,t} \end{cases} \quad (1)$$

$$HDD_{i,y} = \sum_{t=1,t\in y}^{183} HDD_{i,t} \quad (2)$$

$$CDD_{i,t} = \begin{cases} 0 \\ \frac{T_{X,i,t}-T_{b,c}}{4} \\ \frac{T_{X,i,t}-T_{b,c}}{2} - \frac{T_{b,c}-T_{N,i,t}}{4} \\ T_{M,i,t} - T_{b,c} \end{cases} \text{if} \begin{cases} T_{b,c} \geq T_{X,i,t} \\ T_{M,i,t} \leq T_{b,c} < T_{X,i,t} \\ T_{N,i,t} \leq T_{b,c} < T_{M,i,t} \\ T_{b,c} \leq T_{N,i,t} \end{cases} \quad (3)$$

$$CDD_{i,y} = \sum_{t=1,t\in y}^{182} CDD_{i,t} \quad (4)$$

The symbols used in equations (1)-(4) have the following meaning:

With $T_{b,h} = 15.5^{\circ}C$ – Base temperature for calculation of HDD
With $T_{b,c} = 22^{\circ}C$ – Base temperature for calculation of CDD
$T_{Mi,t}$- Mean temperature in cell i in day t
$T_{X,i,t}$- Maximum temperature in cell i in day t
$T_{N,i,t}$- Minimum temperature in cell i in day t
$HDD_{i,t}$, $CDD_{i,t}$ – HDD and CDD in cell i and day t
$CDD_{i,y}$, $CDD_{i,y}$ - HDD and CDD in cell i and year y

This analysis was performed on both decadal means as well as extremes. The decadal means, corresponding to longer term trends, were based on 10-year means to account for climate variability for all three temperature variables, T_{mean}, T_{min} and T_{max} (i.e. 2050 is the 2046–2055 mean).

The extreme HDD and CDD levels were calculated for the cold and warm months of Jan-Mar and Jun-Aug respectively, also for 10-year periods wherefore the 'extreme' term here refers to 10-year return period statistics. For these periods, both the inter-model mean as well as the inter-model min/max was calculated per grid cell and then aggregated to country scales using the minimum value for each cell regardless of the model. The reasoning in using both the inter-model means and min/max is due to the limitations in using multi model means for extremes, whereas the min/max for single models might reflect model deficiencies. The combination of these metrics is therefore needed for an optimal analysis. The reason for the use of HDD minima and CDD maxima is due to the expected sign of change (assessed but not shown) with global warming (see section 2.2).

Further, to investigate the impact of season length, a sensitivity analysis was performed for both the heating and cooling demands varying the duration 1–7 months around the centre-month for the GCM-RCM model combination with the highest and lowest heating and cooling demand levels (RCA4-HAD and RACMO22-EC respectively).

2.3. Applying weights to heating and cooling degree days[1]

Following the calculation of HDDs and CDDs for every cell in EU in 5-year steps between 2010 and 2050, weights were applied to account for population density as a measure of demand rates as also seen in e.g. [9]. The population weights were based on the Geostat dataset from Eurostat [42], having the finest resolution currently available for Europe. The weighting approach was applied since the spatial distribution of aggregated building heating/cooling demands depend not only on HDDs/CDDs but also on the number and density of buildings. For example, the heating demand decreases with increasing temperatures in both northern Norway and in southern Germany. However, due to differences in population density, southern Germany poses a substantially stronger influence on the demand in Germany as compared to the influence of northern Norway within Norway.

The weight of the cells are calculated as follows:

$$w_i = \frac{\sum_{j\epsilon i} P_{i,j}}{P_k} \quad (5)$$

Where:
w_i – weight of RCM grid cell (i) (located within country k)
$P_{i,j}$ – Population of 1x1 km cell j which belongs to 12.5x12.5 km cell i
P_k – Population of country k
i – 12.5x12.5 km cell
j – 1x1 km cell
k – EU countries

[1] All the resulting data are available online as supplementary material.

The population data within 1x1 km cells are obtained from GEOSTAT 2011 grid dataset (version updated in 2016) [43].

2.4. Absolute changes in heating and cooling demands

The demand change ratios have the advantage of applicability in energy systems modelling but in essence say little about the absolute energy consumption for heating and cooling on either grid or country level scales. To accommodate this deficiency and highlight where climate change can vastly impact the energy consumption used for heating and cooling, the 2050/2010 demand change ratios were combined with the current and most recent (2017) absolute levels (Mtoe) of service sector and residential heating and cooling from the ODYSSEE database [44], which for some countries included the "n.a." abbreviation. A key assumption here is of course the stationarity of these levels towards, but including building stock and HVAC scenarios is outside the scope of this study.

3. Results

3.1. Temperature projections

The results from the analysis of the mean European near-surface temperatures from the eight-model CORDEX RCM ensemble (see Table 1) are shown in Fig. 1. The annual historical means (Fig. 1a) are included here for reference purposes, and show the expected north–south gradient and the influence of topography. As expected, the annual anomalies (Fig. 1b-1e) show an increasing warming with the RCP scenario (RCP2.6/RCP4.5) and distance into the future (2026–2035/2046–2055). Further, these plots also show an increased relative warming compared to the reference period towards the north-eastern parts of Europe as well as for higher altitude areas such as the Alps, the Pyrenees, the Iberian Peninsula and the Carpathian mountains. As a measure for model robustness, the inter-model temperature standard deviations for each period and RCP have been plotted (Fig. 1b – 1e, inserts) showing a general trend towards a higher robustness for the RCP4.5 model ensemble as opposed to the RCP2.6 ensemble. This could be explained by the relatively weak trend in the RCP2.6 scenario as often completely omitted from RCM climate change studies [45,46]. Further, higher inter-model deviation is seen for mountainous regions. For the results on T_{max} and T_{min}, see the Appendix and Figs. A.1 and A.2.

3.2. Heating and cooling demand changes

Heating demand ratios from 2010 to 2050 for both the trend analysis (10-year mean - RCP2.6 and RCP4.5) and the extreme analysis (10-year min/max levels – RCP4.5) are presented in Fig. 2. On a general level, and unsurprisingly considering the warming trend represented by the RCP scenarios, the trend in heating demand decreases and more so for RCP4.5 than for RCP2.6. A few Mediterranean countries, Malta, Italy, Greece, Cyprus and Bulgaria, however exhibit positive trend changes. For the model ensemble mean (Fig. 2, left), the mean decrease ratio from 2010 to 2050 is approximately 0.9 for both the trend and mean analyses, whereas for the ensemble minimum (Fig. 2, right) the trend analyses show ratios of 0.87–0.88 and the extreme analysis shows a ratio of 0.69.

The changes in cooling demand ratios per country is consistently positive as seen in Fig. 3. Results are only included when a model mean of ten cooling degree days is exceeded since lower levels resulted in improper results for countries with a low level of CDD. For the model ensemble trend mean, RCP2.6 and RCP4.5

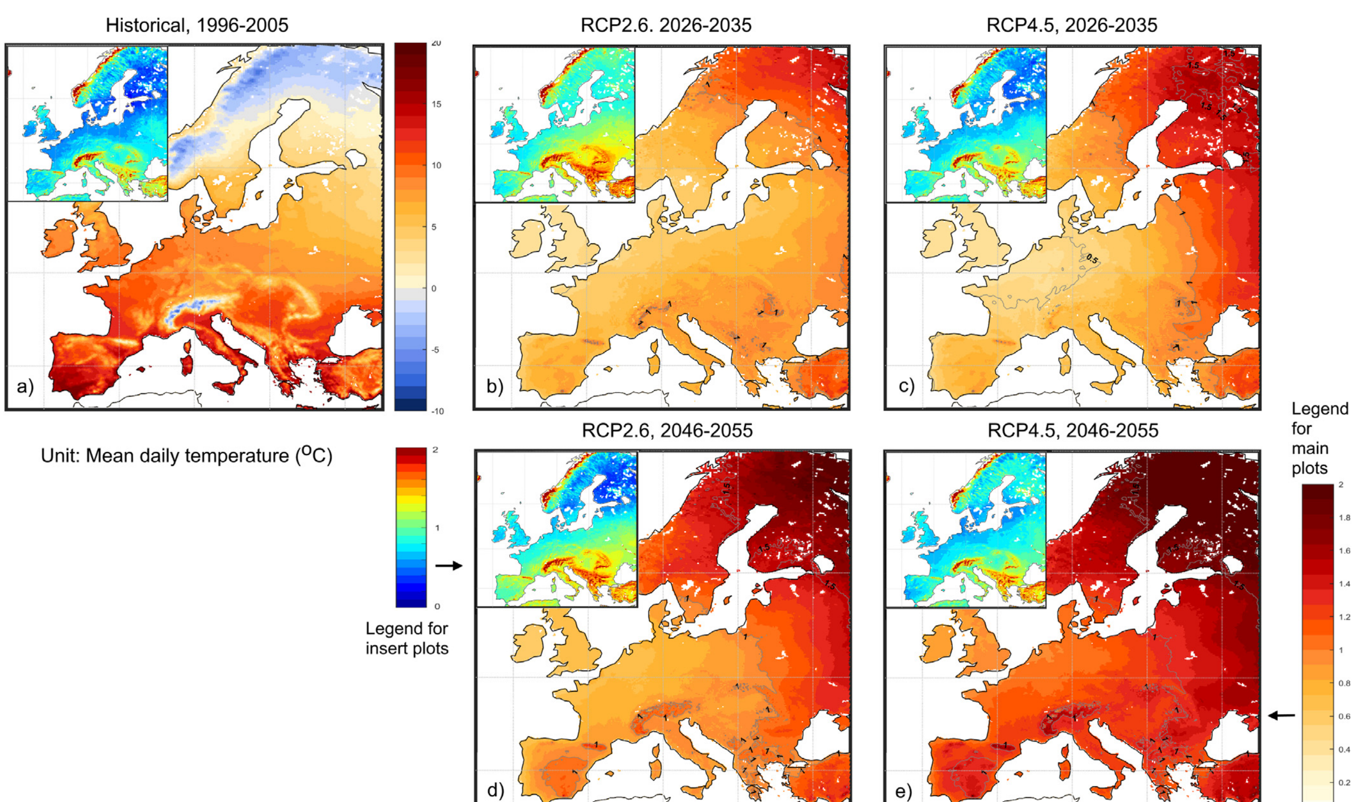

Fig. 1. Plot a): 1996–2005 mean temperature (T_{mean}) from the eight-model CORDEX ensemble. Plots b)-e): Corresponding anomaly values (relative to historical period) for RCP2.6 (left) and RCP4.5 (right) for 2026–2035 (top) and 2046–2055 (bottom) including contour lines for the levels of 0.5, 1 and 1.5 °C. Top-left insert plots b)-e): The corresponding inter-model T_{mean} standard deviation for each scenario and period.

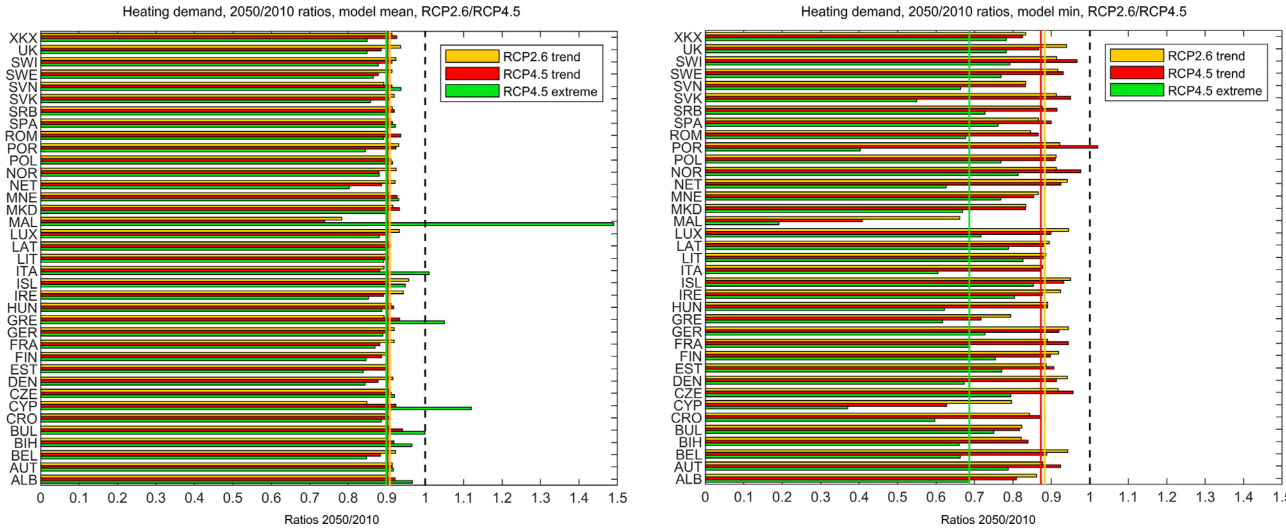

Fig. 2. Heating demand change ratios for 2050/2010 for the temporal trend and extreme analyses for the RCP2.6 (trend only) and RCP4.5 climate scenarios and the model mean (left) and model minimum (right) respectively.

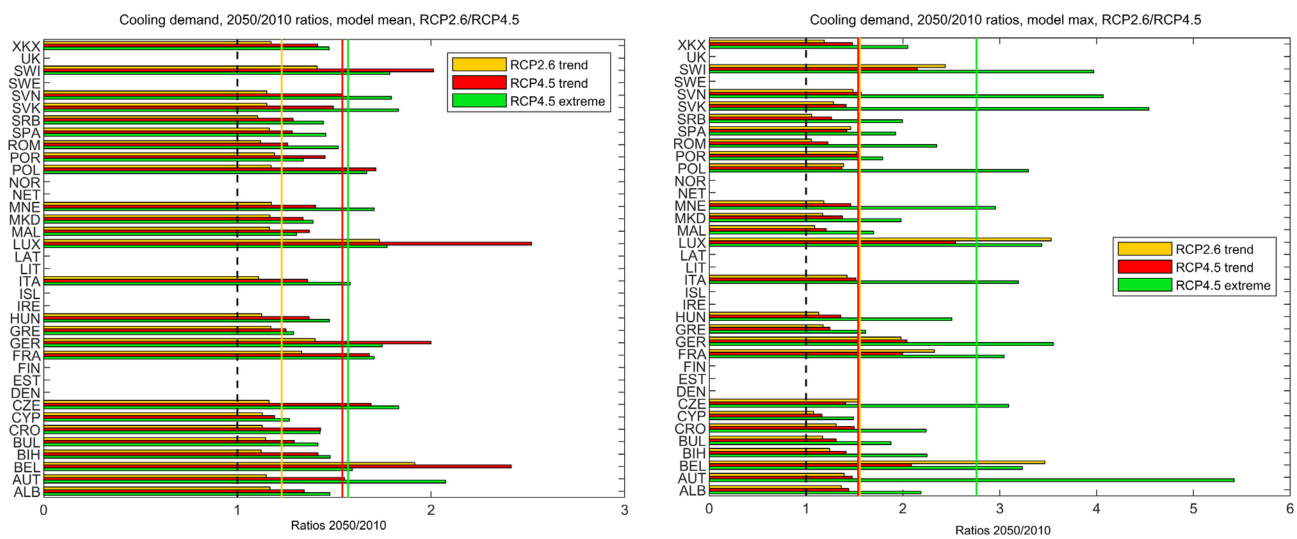

Fig. 3. Cooling demand change ratios for 2050/2010 for the temporal trend and extreme analyses for the RCP2.6 (trend only) and RCP4.5 climate scenarios and the model mean (left) and model maximum (right) respectively. Results are for countries only where a CDD average above 10 was present to avoid presenting high changes based on either a negligible reference level or a few grid cells only.

exhibit ratios of 1.23 and 1.54 respectively, whereas the model ensemble mean extreme equals 1.52 (Fig. 3, left). For the model ensemble max, the RCP2.6 and RCP4.5 trend ratios are 1.56 and 1.54, whereas the model ensemble max extreme is 2.76 (Fig. 3, right). The countries with the highest model ensemble max levels include e.g. Austria, Slovakia, Slovenia and Switzerland. The sensitivity of season length on resulting heating and cooling demand ratios are seen in Fig. A.3 and in general show no impact for durations beyond three months whereas for a one-month duration the ratio is highly dependent on GCM/RCM model combination and country in question.

3.3. Distributed heating and cooling demands

The distributed changes in heating and cooling demand ratios from 2010 to 2050 (RCP4.5) for both the mean/trend and the extreme min/max analysis are seen in Figs. 4 and 5 respectively.

For model ensemble mean heating demands (Fig. 4, top), the largest decrease is seen for Western and Northern Europe whereas Mediterranean and Eastern European countries exhibit a lower degree of change. Investigating the results at the grid scale reveals that mountainous areas and Mediterranean shorelines are the areas with the lowest degree of change whereas large shares of land exhibit change levels of approximately 0.8–0.9. For model minimum heating demands, another pattern of results emerges: Here, the lowest levels at grid scales are seen for Southern Europe especially the lower half of the Iberian peninsula, Italian shorelines and the lowlands of Hungary, Serbia, Romania, Bulgaria and to some extent also the Benelux countries, and these patterns also affect the country mean results. These areas and countries show change ratios of 0.35 to 0.65 on a country level. Northern and North-Western Europe shows a lower degree of change in the order of 0.7–0.9.

The Cooling demand change ratios from 2010 to 2050 are seen to be highest in Northern Europe such as Norway, Sweden, Finland and Ireland, whereas areas of higher topography such as the Carpathians, Massif Central and the Ardennes also show high levels. The major mountain chains such as The Alps, The Pyrenees

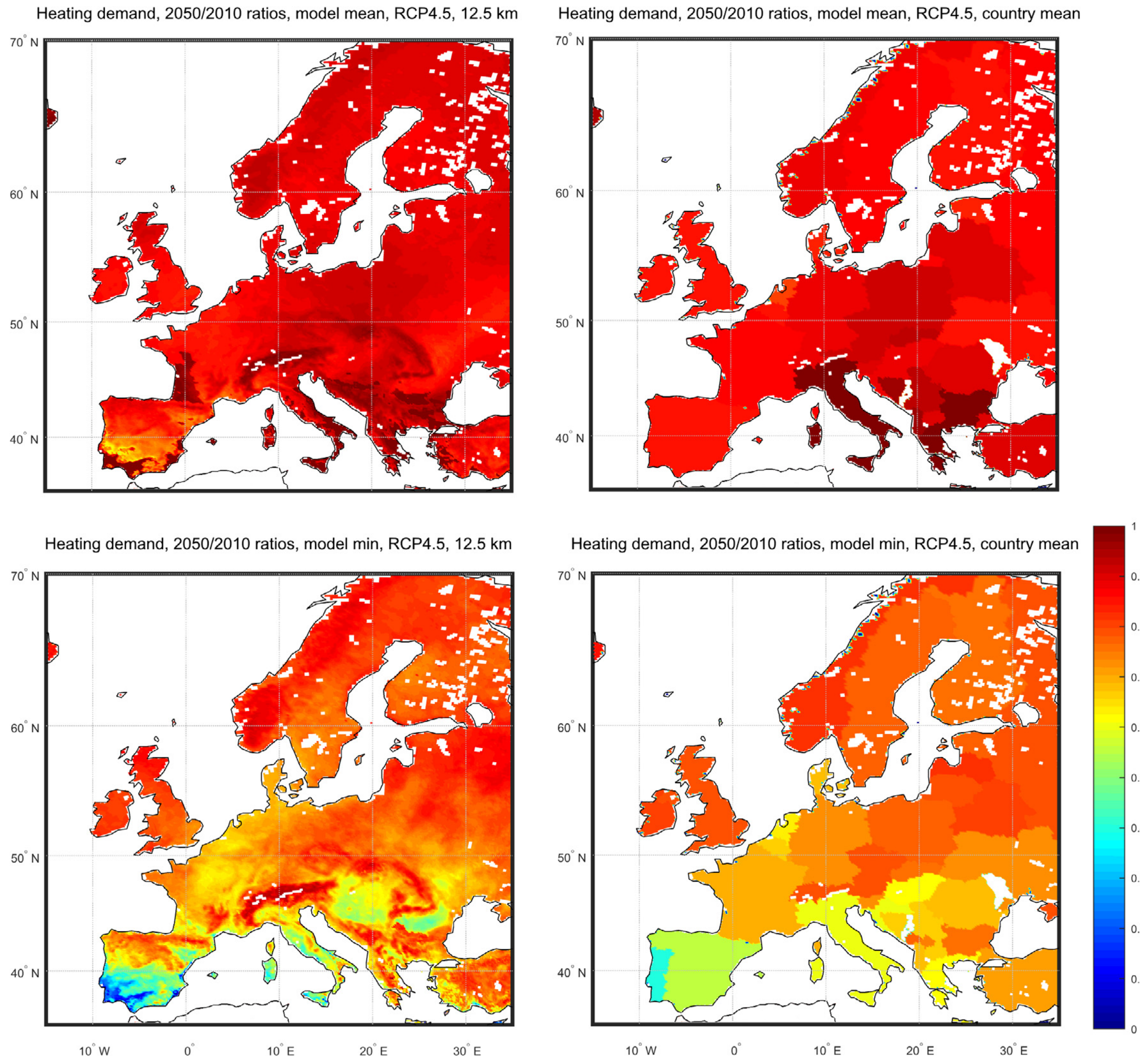

Fig. 4. Heating demand change ratios for 2050/2010 for RCP4.5 on grid- and country level scales and for both the inter-model mean and minimum.

and large parts of Norway however stand out without any resulting levels due to the lack of CDDs, i.e. division by zero. A much stronger increase in cooling demand is seen for the model max results of, on average, 3.75 compared to the respective model mean of 1.74. Excluding countries with a CDD mean below 10 as also seen in Figs. 4-6, which significantly affects the country-level results due to the impact of a few grid cells only, results in corresponding levels of 2.76 and 1.57 respectively. For the individual countries (see table 2), change ratios up to 3.24 (Norway) and 11.24 (Ireland) are seen for the model ensemble mean and max respectively, but assigning the threshold of 10 for the CDD mean, the corresponding levels are 2.07 and 5.42 (both Austria)

3.4. Trends vs. extremes and model ensemble means vs. corresponding min/max

Fig. 6 depicts the relationship per country in demand change ratios between trends (10-year means) and extremes (10-year heating min and cooling max level) for the model ensemble mean and the model ensemble min/max (calculated per cell and aggregated to country scale). In the figure, the 1:1 level as highlighted (100% correlation) as well as the level of 1 (no change).

For the model mean heating demand (Fig. 6, left, blue), there is a high resemblance per country between the demand change ratios for the trend and extreme analysis, with a slight tendency for the extreme analysis to even show positive levels – these are the Mediterranean countries also mentioned in section 3.2. Or in other words, for the model ensemble mean the change ratios are similar for the extreme levels as compared to the trend levels. For the ensemble model minimum on the other hand (Fig. 6, left, red), the extreme analysis shows a higher decrease as compared to the trend analysis.

For the cooling demands the pattern is similar although addressing maxima: the ensemble model mean analysis shows comparable change ratios between the trend and extreme analyses (although, again, a few countries, Luxembourg and Belgium, show higher levels for the trend analysis) and the ensemble model maximum analysis shows significantly higher change ratios for the extreme analysis. In summary, changes in heating and cooling demands for both the trend analysis (10-year means) and the extreme analyses (10-year min/max) are somewhat similar for the model ensemble mean whereas the model ensemble min/max shows a higher degree of change for the extreme analysis.

3.5. Absolute service and residential sector heating and cooling demands

The absolute levels in heating and cooling demands for the EU28 countries (+SWI, SRB and NOR) are shown in Fig. 7. Much as expected, high heating and cooling demand ratios, as in Figs. 2

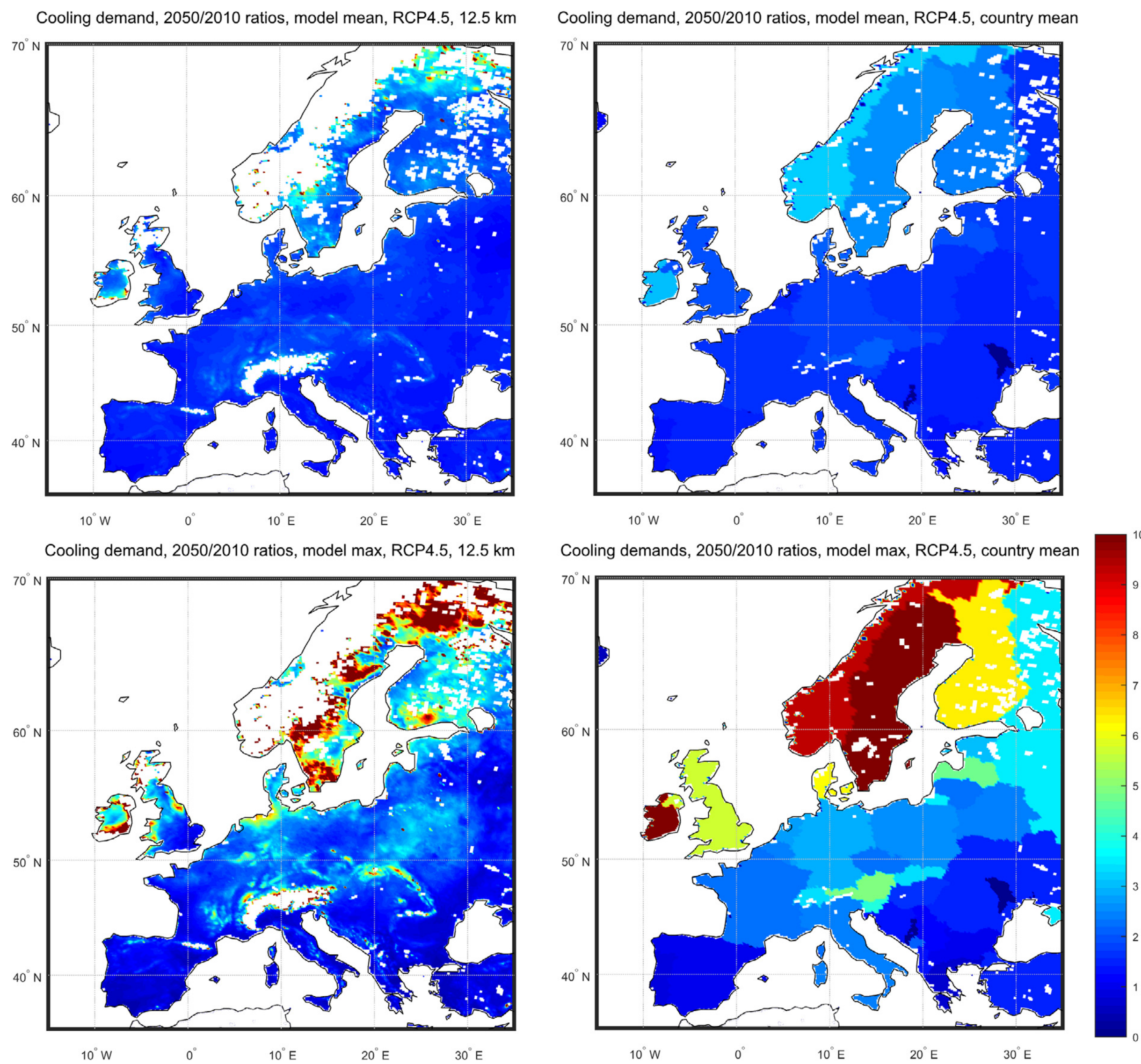

Fig. 5. Cooling demand change ratios for 2050/2010 for RCP4.5 on grid- and country level scales and for both the inter-model mean and maximum. Note the areas without results (no cooling demand in 2010 and/or 2050), that affect country-level results.

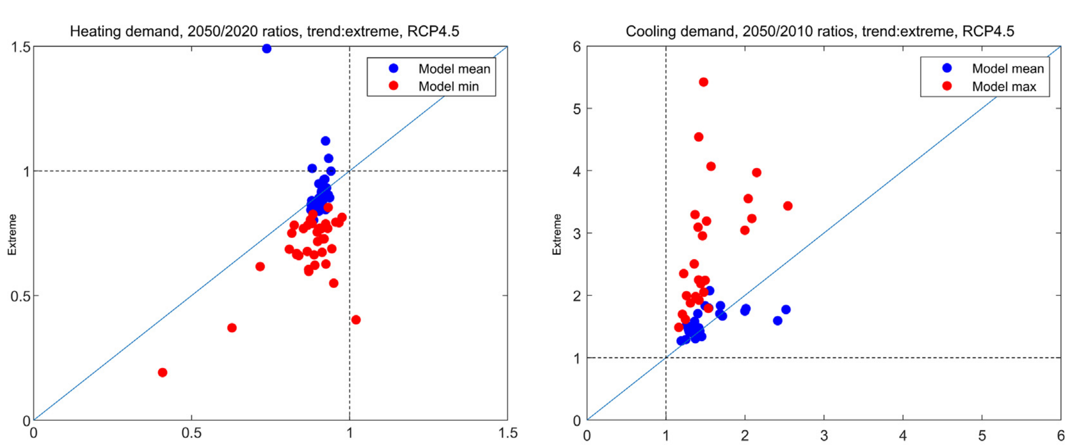

Fig. 6. The heating (left) and cooling (right) demand 2050/2010 ratios between the temporal trend and extreme analyses for both the inter-model mean and mininima/maxima. The same models as for Fig. 3 were omitted here (see Fig. 3 caption).

Table 2
Three-letter country abbreviations and relative changes for heating/cooling demands for RCP2.6/RCP4.5, the inter-model mean/max and temporal trends/extremes. Bold values are for countries with inter-model average CDD levels below 10 (see Fig. 4 caption). These are omitted from Figs. 3 and 6.

		Cooling						Heating					
		2050/2010 Demand ratios						2050/2010 Demand ratios					
		RCP2.6 Model mean Trend	RCP2.6 Model max Trend	RCP4.5 Model mean Trend	RCP4.5 Model max Trend	RCP4.5 Model mean Extreme	RCP4.5 Model max Extreme	RCP2.6 Model mean Trend	RCP2.6 Model max Trend	RCP4.5 Model mean Trend	RCP4.5 Model max Trend	RCP4.5 Model mean Extreme	RCP4.5 Model max Extreme
1	ALB	1.17	1.36	1.35	1.44	1.48	2.19	0.90	0.86	0.92	0.81	0.97	0.69
2	AUT	1.15	1.39	1.55	1.48	2.07	5.42	0.91	0.88	0.91	0.92	0.92	0.79
3	BEL	1.92	3.47	2.41	2.09	1.59	3.23	0.92	0.94	0.88	0.89	0.85	0.66
4	BIH	1.12	1.24	1.42	1.41	1.48	2.25	0.90	0.82	0.92	0.84	0.97	0.66
5	BUL	1.15	1.17	1.29	1.31	1.42	1.88	0.90	0.82	0.94	0.82	1.00	0.75
6	CRO	1.13	1.31	1.43	1.50	1.43	2.24	0.90	0.84	0.91	0.87	0.89	0.60
7	CYP	1.13	1.08	1.19	1.16	1.27	1.49	0.85	0.80	0.92	0.63	1.12	0.37
8	CZE	1.16	1.53	1.69	1.41	1.83	3.09	0.91	0.92	0.91	0.96	0.92	0.79
9	DEN	***2.39***	***1.62***	***2.47***	***1.10***	**2.14**	**6.53**	0.92	0.94	0.88	0.91	0.84	0.67
10	EST	***1.51***	***1.74***	***4.18***	***2.92***	**1.85**	**3.71**	0.90	0.89	0.90	0.91	0.84	0.77
11	FIN	***1.67***	***1.92***	***6.15***	***2.92***	**2.39**	**6.72**	0.90	0.92	0.89	0.90	0.85	0.75
12	FRA	1.33	2.32	1.68	2.00	1.71	3.04	0.92	0.89	0.88	0.94	0.87	0.69
13	GER	1.40	1.98	2.00	2.04	1.75	3.55	0.92	0.94	0.90	0.92	0.89	0.73
14	GRE	1.17	1.18	1.25	1.25	1.29	1.61	0.89	0.79	0.93	0.72	1.05	0.62
15	HUN	1.13	1.13	1.37	1.36	1.47	2.50	0.91	0.89	0.92	0.89	0.89	0.62
16	IRE	***16.53***	***12.91***	***3.11***	***1.19***	**3.10**	**11.24**	0.94	0.92	0.89	0.88	0.85	0.80
17	ISL	***9.16***	***12.60***	***1.18***	***1.57***	**1.16**	**1.53**	0.96	0.95	0.90	0.93	0.95	0.85
18	ITA	1.11	1.42	1.36	1.51	1.58	3.19	0.89	0.88	0.88	0.87	1.01	0.60
19	LAT	***1.40***	***1.54***	***3.07***	***2.71***	**2.01**	**5.29**	0.91	0.89	0.91	0.88	0.90	0.79
20	LIT	***1.18***	***1.46***	***2.30***	***2.04***	**1.71**	**3.10**	0.90	0.89	0.90	0.88	0.89	0.83
21	LUX	1.73	3.53	2.52	2.54	1.77	3.43	0.93	0.94	0.90	0.90	0.88	0.72
22	MAL	1.17	1.09	1.37	1.21	1.31	1.70	0.78	0.66	0.74	0.41	1.49	0.19
23	MKD	1.17	1.17	1.34	1.38	1.39	1.98	0.92	0.83	0.93	0.83	0.90	0.67
24	MNE	1.18	1.18	1.40	1.46	1.71	2.95	0.91	0.87	0.93	0.85	0.93	0.77
25	NET	**2.07**	**3.29**	**2.66**	**2.00**	**1.53**	**3.51**	0.92	0.94	0.89	0.92	0.80	0.63
26	NOR	**1.34**	**0.93**	**4.24**	**2.08**	**3.24**	**9.42**	0.92	0.91	0.88	0.98	0.88	0.81
27	POL	1.17	1.39	1.72	1.37	1.67	3.30	0.90	0.91	0.91	0.91	0.92	0.77
28	POR	1.19	1.52	1.45	1.54	1.34	1.79	0.93	0.92	0.92	1.02	0.84	0.40
29	ROM	1.12	1.05	1.26	1.22	1.52	2.35	0.90	0.85	0.94	0.87	0.89	0.68
30	SPA	1.17	1.46	1.28	1.42	1.46	1.92	0.92	0.91	0.91	0.95	0.86	0.55
31	SRB	1.11	1.06	1.29	1.26	1.44	1.99	0.89	0.83	0.91	0.83	0.94	0.66
32	SVK	1.15	1.28	1.50	1.42	1.83	4.54	0.91	0.88	0.92	0.91	0.90	0.73
33	SVN	1.15	1.48	1.54	1.57	1.80	4.07	0.91	0.87	0.92	0.90	0.92	0.76
34	SWE	***1.27***	***1.41***	***2.76***	***1.04***	**2.57**	**9.89**	0.91	0.92	0.88	0.93	0.86	0.77
35	SWI	1.41	2.44	2.01	2.15	1.79	3.97	0.92	0.91	0.91	0.97	0.88	0.79
36	UK	***3.31***	***3.12***	***2.39***	***1.45***	**1.90**	**6.16**	0.94	0.94	0.89	0.87	0.85	0.78
37	XKX	1.17	1.19	1.42	1.48	1.47	2.05	0.91	0.83	0.93	0.82	0.85	0.78

and 3, do not lead to higher absolute levels and therefore larger countries with high demands dominate the figure. For heating demands, the general trend follow the reductions of factor 0.8–0.9 for the trends whereas the model minima surprisingly shows significant reductions for RCP2.6 as seen for e.g. Italy, Germany and France. For cooling demands, some countries are projected to experience vast increases, based on the model mean, such as Spain, France and UK although the latter is based on a large model spread (see table 2). For the model maxima absolute cooling demand projections, single countries such as France, Switzerland and Spain can exceed a doubling. From the results it can also be seen that the residential sector by far dominate the heating demands whereas opposite is the case for cooling demands dominated by the service sector.

4. Discussion

The present paper analyses the European-scale changes of both trends and extremes in heating and cooling demands as a consequence of the change in outdoor temperatures for eight climate models under two climate scenarios using the highest available spatial as well temporal resolutions for each data set in question.

With regards to the climatic data used in calculating heating and cooling demands, the significant, and well-documented [45,46], range in outcomes from the RCM ensemble for both trends and extremes, as represented here by the inter-model coefficient of variation, justifies the use of multiple climate models in the context of highlighting uncertainty levels to decision-makers. The spread between RCMs is, in particular, evident with regards to the extremes (Figs. 2, 3 and 6) as is also seen in [47]. The well-known challenges for climate models in resolving processes along coastlines and higher topographical areas, even for high-resolution RCMs, which is evident as inter-model spread also affects the countries with higher shares of these attributes. This is highly evident for heating demands over e.g. Italy, Greece and Bulgaria and also affects the country-scale results (Fig. 4). Despite the uncertainties stemming from the inter-model spread, the results clearly depict that some countries and regions will experience severe changes in heating and cooling demands for certain periods and seasons which the energy systems in question need to be able to account for. The lack of full energy consumption data for all of EU28 (+3 countries) for heating and cooling purposes within the residential and service sectors, highlights the problem of data accessibility, quality and underlying assumptions when performing larger scale studies [48].

Further, the choice of RCP scenario for projecting future changes further expands the range of outcomes and adds to the complexity and knowledge base which needs to be transferred from research to end-users. From Figs. 1 to 3, it is evident that the country-

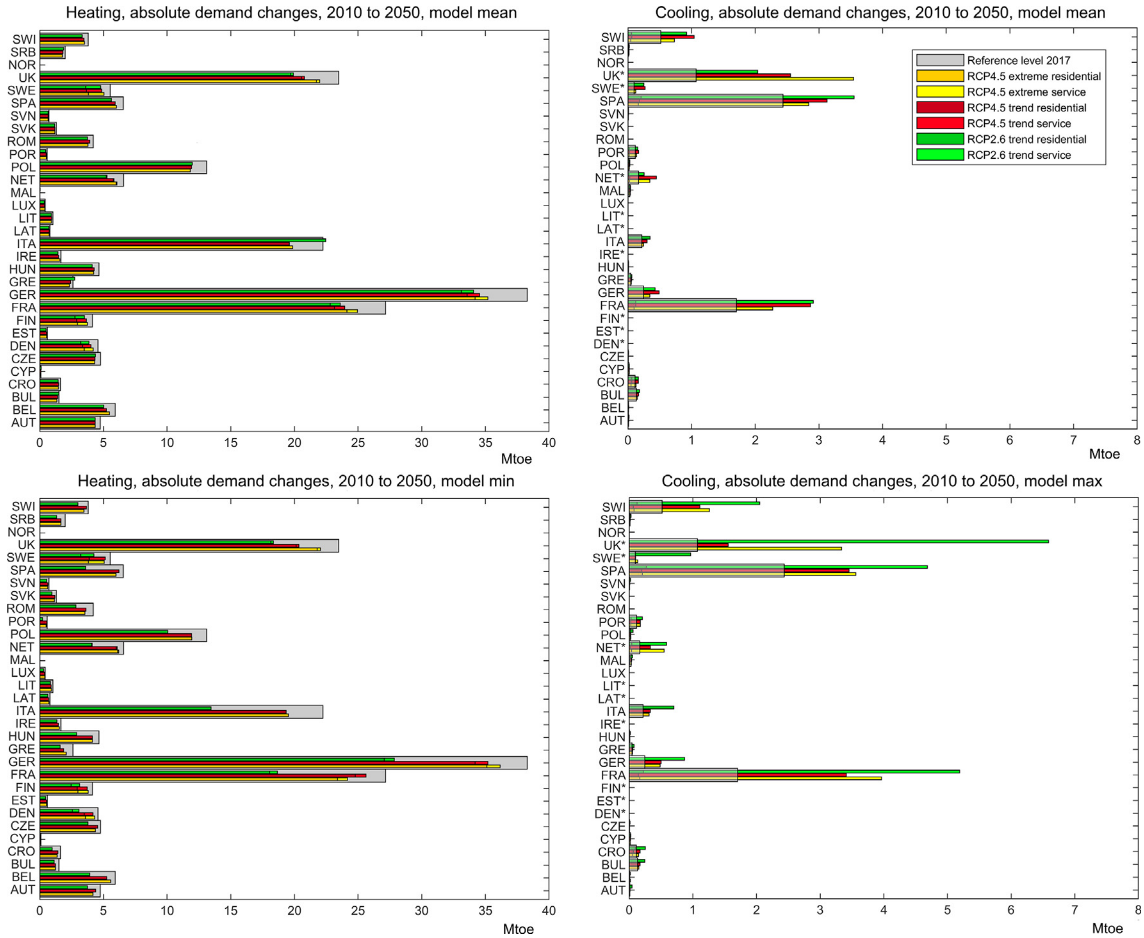

Fig. 7. Absolute levels in residential and service sector heating and cooling demands for EU28 countries (+SWI, SRB and NOR) based on the relative 2010 to 2050 change ratios and the 2017 energy consumption from [44]. Some countries included "n.a." data and countried marked with an "*" correspond to the countries in bold font in Table 2 where the CDD model average is below 10.

scale results for smaller geographical regions, such as Cyprus and Malta in the Mediterranean with higher model discrepancies, induce a higher uncertainty, as caused by the spread in RCM predictions which are not evened out due to the small number of grid cells covering the countries in question.

Also, a high single influence from single RCM models, with output diverging from the ensemble model mean is apparent, as seen for e.g. Latvia and Lithuania, where one RCM with much higher CDD levels compared to the other models, and a slightly higher 2030 level compared to 2050, causes an apparent drop from 2030 to 2050 (not shown).

For the future RCP scenarios 6.0 and 8.5 [25] (not addressed here), the former would likely impose heating and cooling demand levels comparable to RCP4.5, as decided by the resulting projected temperatures by 2050, whereas RCP8.5 would inflict highly reduced levels of heating demand and vice versa for cooling demand. The net energy effect, as balanced by decreased heating demand and increased cooling demand, has been shown to vary with the geographical location of the study area in question [49]. Similar trends of decreasing heating demands and increasing cooling demands have been found by [50] where, also, an increased risk of overheating in more extreme higher-range temperatures was detected under projected future climate change scenarios.

The impact of climate change and the use of projected future temperatures to calculate the resulting relative changes in trends and extreme heating and cooling demands can be directly used to scale (up or down) the existing space heating and cooling demands on e.g. country scales to thereby obtain future levels. In doing so in the present study, it is assumed not to affect the domestic hot water demand. Such a scaling implies the assumption that the inhabitants of buildings maintain the same behaviour over the analysed period i.e. neglecting the rebound effect [51], internal set temperature, heating and ventilation habits etc. [52]. For example, while an increase in outdoor temperatures could translate into reduced heating demand, it could also lead to higher heating set points, which could mitigate or offset the direct effects. Scaling of existing space heating and cooling demands could be applied in future studies to residential, commercial, public buildings, etc. but applying the same procedure to industrial facilities should be done with caution since space heating accounts for very small share of heating demand in industrial facilities.

Changes in the outdoor temperature affects the profitability of heat saving measures. Namely, an increase in the outdoor winter temperature can be seen as "free" heat savings and thus make additional heat savings more expensive; the opposite applies for a reduction in outdoor temperature in winter (the converse is the case in summer). Another effect of increasing outdoor temperatures is an increase in the coefficient of performance (COP) of air-to-air heat (and cooling) pumps, i.e. they become more efficient [53]. On the other hand, the economics of both heat supply (e.g. boilers) and demand side (e.g. insulation) measures is adversely affected by reduced winter heating demands, either in terms of length, magnitude, or both. For all of these effects, energy systems analysis should be applied at relevant geographical levels in order to explore these phenomena in the context of rapidly-changing national energy systems. This field of research is a part of ongoing work as implemented in e.g. the TIMES-DK energy model [54].

When calculating heating and cooling demand changes on a national level, the present approach takes into account that not all the regions have the same heating/cooling demands. For example, densely populated areas in West Germany have higher weights compared to sparsely populated areas in the eastern parts of Germany. On the other hand, the presented approach implicitly assumes that the distribution of heating demand within a country remains as in 2010 throughout the analysed period. It is well known that sub-national differences in the building stock and economic activity, including migration, are significant influencing factors for the distribution and future development of the residential space heating demand [55]. Even though a national-level redistribution of heating demand could happen in the future, maybe even itself partly motivated by climate change, the authors consider them outside of the scope of the paper. In the context of calculated demand changes, a national-level geographical redistribution of demands will mostly affect countries of greater length in the latitudinal direction (i.e. north to south), such as Sweden and Italy, or for countries with both inland/coastal climates, e.g. France.

Although outdoor temperature is an important externally-given factor, the actual heating and cooling demands depend on user behaviour, the buildings' thermal characteristics and potential smart technologies affecting the energy consumption. Research has shown that user behaviour and smart technologies have a comparable importance [56]. Behavioural aspects alone can account for up to a 100% variation in household energy demands within the same HVAC technology [52]. The translation of these changes in Degree Days to changes in heating demands will therefore crucially depend on the development in user's behaviour and the degree to which they can be more sensitized to accept flexible energy demand, renewable and energy efficient technologies in the future [57-59]. The issue of future thermal characteristics of the building stock in question is not addressed due to the speculative nature of such a scenario. While most EU member states have ambitious targets in the context of implementing the Energy Performance in Buildings Directive [60], such as all new buildings being passive standard from 2020, there is a large degree of uncertainty about long term improvements in the energy efficiency of buildings [61]. A large challenge in this area is the refurbishment of existing buildings, some of which are protected for reasons of cultural and/or social interest [62]. Also, the urban heat island effect [63] could be accounted for in future studies. In summary, the results presented here should therefore be interpreted as indicative, as they essentially 'freeze' both of these two dimensions, while instead illustrating the impact of climate change on both trends and extremes and the consequence of assuming constant climate on assessments of future energy saving calculations concluding that future changes in heating and cooling demands need to be accounted for.

The method employed here derives robust estimates of future European heating and cooling demands, both at the highest possible climate model resolution of 12.5 km^2 and at the national level, and the results illustrate the implication of assuming a constant climate on the assessments of future energy saving calculations. The relative implications of these results for the economic efficiency and relative attractiveness of efficient heat and cooling generation and saving options are clear, but a detailed energy system analysis is required in order to quantify and understand their relative importance.

The study does not address potential future population changes and intra- and international migration as potential future drivers of changing energy demands which could be a significant factor in countries with a large north–south extent and those with both coastal and inland climates. In addition, the method overlooks future building thermal characteristics and user behaviour, both of which will be crucial in understanding the way in which, and where, European heating and cooling energy service demands develop in the future. These aspects could form the basis of further future research.

5. Conclusions

Against a background of uncertainty about future climate and the most cost-efficient approach to decarbonize the heating sector, the present paper analyses the effects of future temperature changes in trends and extremes on space heating and cooling demands in European buildings using population density as a proxy for spatial distribution of demands. The analysis is performed towards 2050 for two low-to-medium GHG emission climate scenarios (RCP2.6 and RCP4.5) and eight regional climate models from the CORDEX repository [36].

For mean temperatures, annual anomalies are unsurprisingly shown to predict an increasing warming with the RCP scenario (RCP2.6 and RCP4.5) and distance into the future (2026–35 and 2046–2055). The relative degree of warming increases towards the north-eastern parts of Europe as well as for higher altitude areas such as the Alps, the Pyrenees, the Iberian Peninsula and the Carpathian mountains.

In accordance with the trends of warming, the heating demand decreases throughout the European domain whereas the opposite is the case for the cooling demand. In general also, the demand change ratios decrease or increase, for heating and cooling respectively, at much more significant rates for the analysis on 10-year extreme levels as compared to the 10-year mean trend analysis. From the results, it is also evident that areas with high demands are the main drivers of the change in calculated national heating and cooling demands. All countries in Europe are projected to experience a moderate reduction of relative heating demand trends in 2050 with 2050/2010 ratios of 0.85–0.95 the RCP scenarios addressed here, with the exception of Cyprus and Malta. For cooling demand trends, the main share of countries, in both the base year and projection years, experience increased relative cooling demand ratios in the general range of 1.25–1.5 but with single countries beyond a ratio of 2. Correspondingly, the mean extreme heating demand between countries show a 2050/2010 demand ratio of 0.69 and the country mean cooling demands increase by a ratio of 2.76.

The results on absolute changes from 2010 to 2050 show general reductions in the order of factor 0.8–0.9 compared to the reference level for the heating demands whereas for cooling demands some countries such as France, Spain and Switzerland experience more than a doubling.

CRediT authorship contribution statement

Morten A. D. Larsen: Study lead, conceptualization, methodology, data processing, analysis, most writing, editing and revisions. **Stefan Petrovic:** Conceptualization, methodology, data processing, analysis, writing and revisions. **Andrea M. Radoszynski:** Data processing and analysis. **Russell Mckenna:** Analysis, writing and revisions. **Olexandr Balyk:** Methodology and analysis.

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.

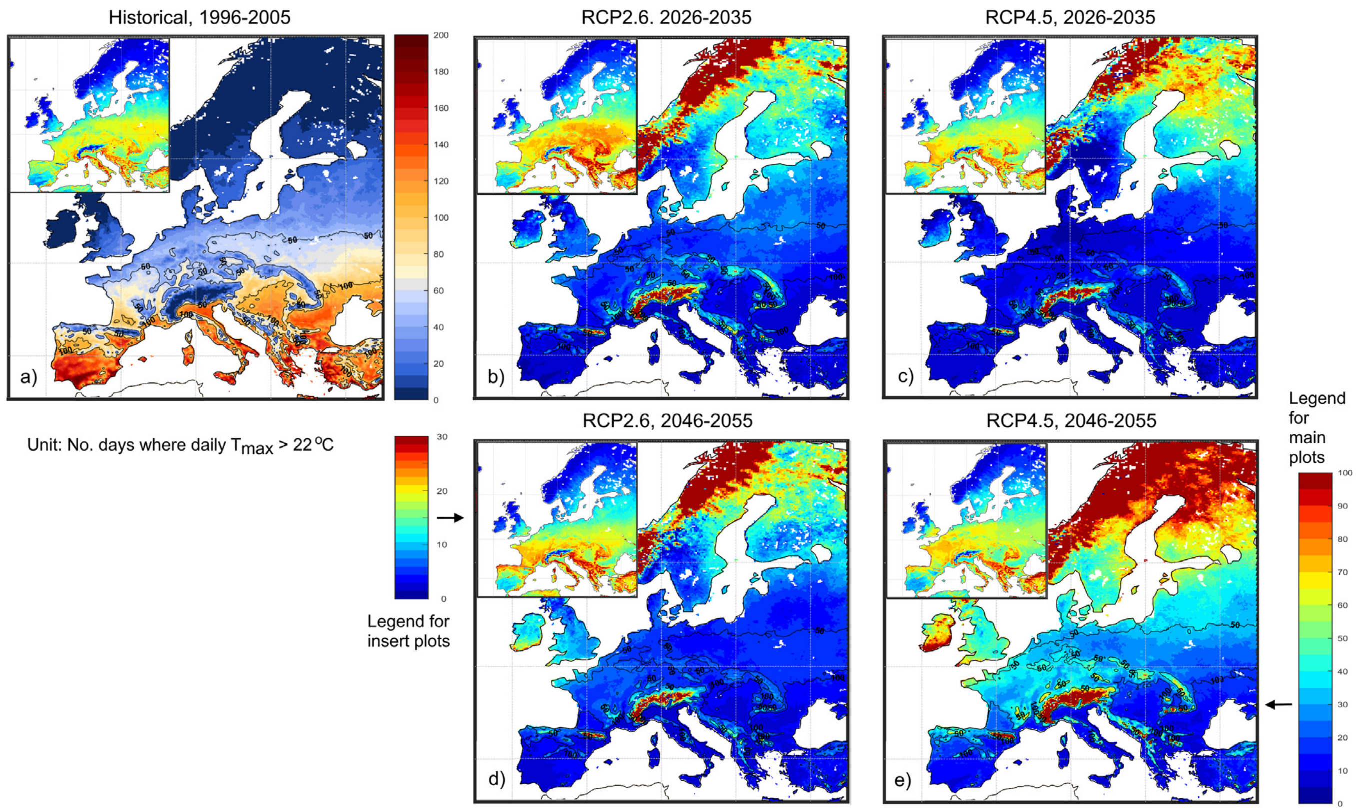
Historical, 1996-2005
RCP2.6. 2026-2035
RCP4.5, 2026-2035
RCP2.6, 2046-2055
RCP4.5, 2046-2055
a)
b)
c)
d)
e)
Unit: No. days where daily Tmax > 22 °C
Legend for insert plots
Legend for main plots

Fig. A1.

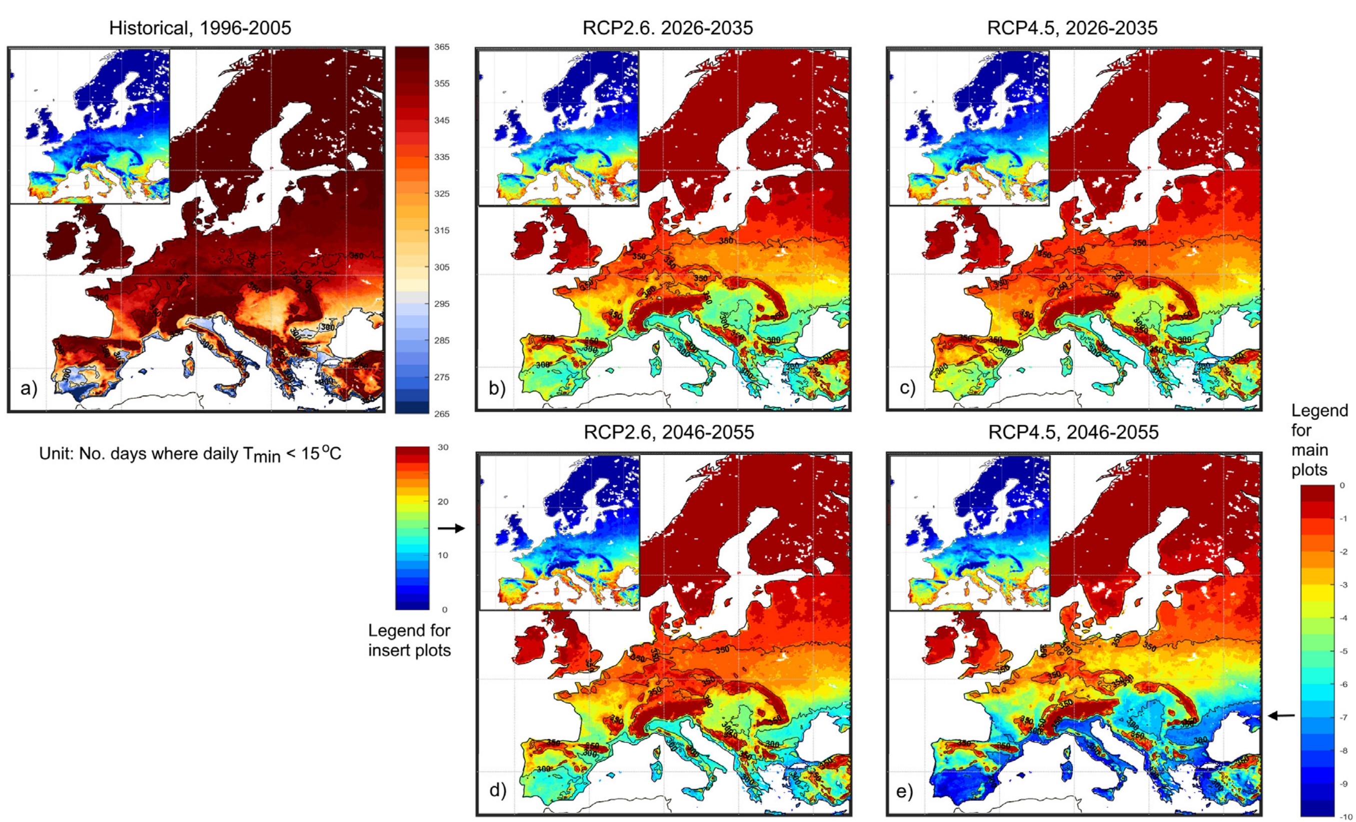
Historical, 1996-2005
RCP2.6. 2026-2035
RCP4.5, 2026-2035
RCP2.6, 2046-2055
RCP4.5, 2046-2055
a)
b)
c)
d)
e)
Unit: No. days where daily Tmin < 15 °C
Legend for insert plots
Legend for main plots

Fig. A2.

Acknowledgements

The work was supported by the REEEM project (grant agreement no. 691739) funded by the Horizon 2020 (LCE) EU research programme.

Appendix

The results from the T_{max} analysis is shown in Fig. A.1 employing the 22°C threshold as used in the HDD/CDD analysis presented below. For the historical period (Fig. A.1a), obvious trends occur varying with the north-south location as well as altitude. In general, occurrences of 100 days or more > 22°C per year are seen in Southern and Eastern Europe whereas the higher areas in e.g. the Alps, the Pyrenees, the Dinaric Alps have few or no similar occurrences (Fig. A.1e-b). Also the distance to larger water bodies is seen to affect the occurrences such as in and around Hungary. In general, for the RCP2.6 and RCP4.5 scenarios, the location of the 50 and 100-day contours move towards the north. For example, the 50-day contour line moves from the areas around Berlin and Paris historically towards the coastal regions of the Benelux countries and the Baltic Sea for the RCP4.5 2046-2055 scenario (Fig. A.1e). The largest changes in T_{max} occur across mountain ranges in Southern Europe, Ireland and all across Norway and to some degree Sweden and Finland. As for T_{mean}, the smallest cross-domain inter-model standard deviation for T_{max} is seen for the historical period followed by RCP4.5 and then RCP2.6 (Fig. A1.b–e, inserts). Further, the largest inter-model spread is seen across central and southern Europe, mostly related to high-topography areas, although the Alps is a notable exception. The large inter-model spread over the Dinaric Alps has also been shown in [46].

The T_{min} analysis results are shown in Fig. A.2. These results employ the 15.5°C threshold as used in the HDD/CDD analysis. As for T_{max}, both the historical and the projected RCP results are mainly dependent on the latitude and topography. Thus, for the historical period, a higher number of days above the T_{min} < 15.5°C threshold is seen in northern Europe and in mountainous regions (Fig. A.2a). In broad terms, the threshold of 350 days/year with T_{min} < 15.5°C is crossing central Europe whereas for mountain ranges, areas are seen as far south as southern Spain, southern Italy, Greece and Turkey. The largest relative changes days/year with T_{min} >15.5°C, increasing with RCP scenario and interest period into the future, occur for southern Europe with changes up to 10% (Fig. A.2b–e). This is natural as the northern regions with a large share of days within the threshold (350-365 days/year), would not experience large relative changes. Concurrently for the projected future, and again correlated with RCP scenario and interest period, the 350 days/year threshold moves northwards reaching the coastal regions of the North Sea and the Baltic sea. With regards to the T_{min} inter-model spread, the highest levels are seen further south in the coastal Mediterranean regions as compared to T_{max} and with minimal differences between RCP2.6 and RCP4.5 (Fig. A.2b–e, inserts).

Fig. A.3 shows the sensitivity of varying the season length in the extreme analysis for the two GCM-RCM model combinations with

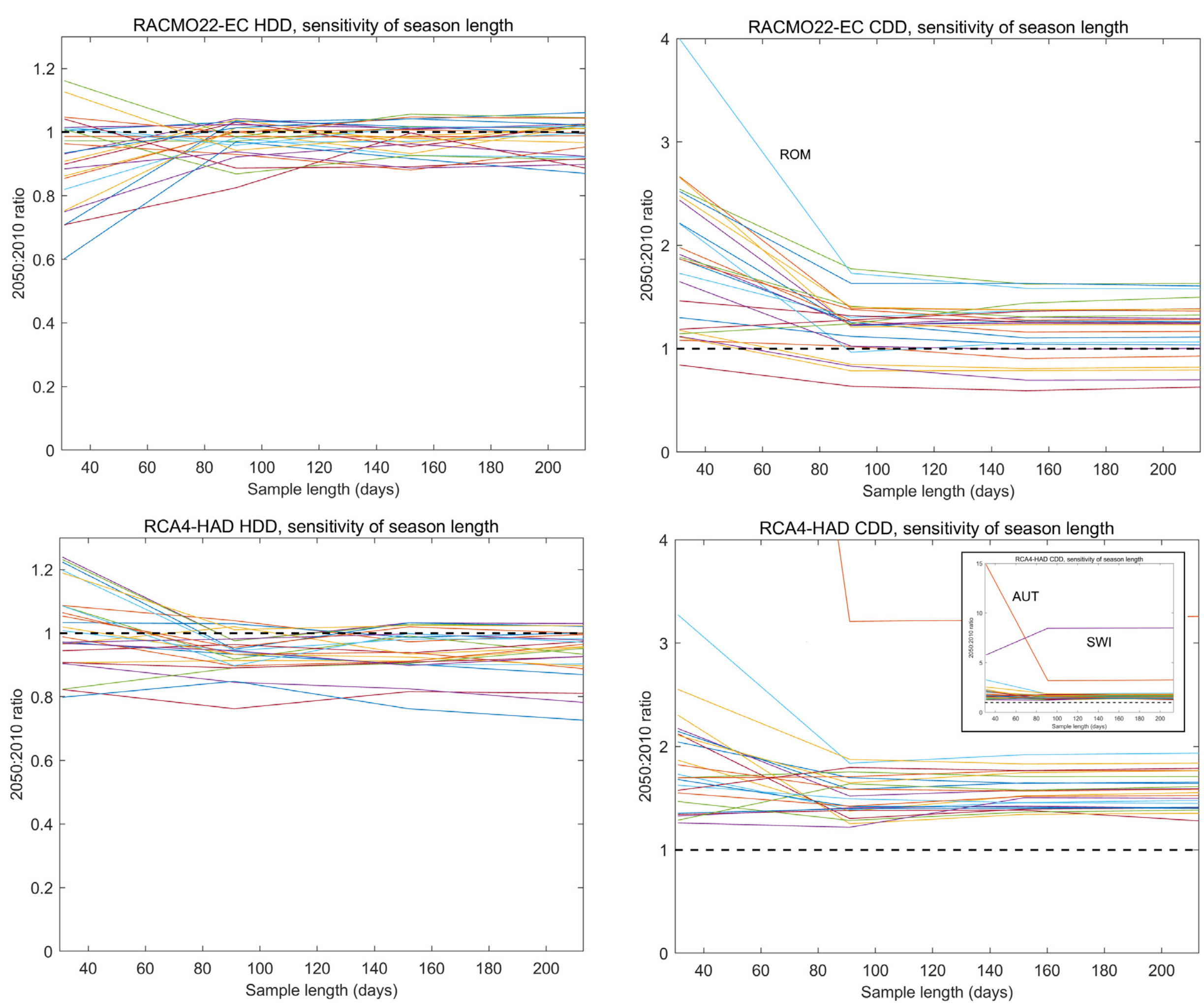

Fig. A3.

the highest and lowest HDD/CDD levels (RACMO22-EC-EARTH and RCA4-HADGEM2) on the resulting 2010-2050 relative heating and cooling demand change ratios. Little to no impact is seen for durations beyond three months, whereas a one-month duration is sensitive but highly dependent on model combination and country in question.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110397.

References

[1] A. Allouhi, Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraouli, Y. Mourad, Energy consumption and efficiency in buildings: current status and future trends, J. Clean. Prod. 109 (2015) 118–130, https://doi.org/10.1016/J.JCLEPRO.2015.05.139.

[2] X. Cao, X. Dai, J. Liu, Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade, Energy Build. 128 (2016) 198–213, https://doi.org/10.1016/J.ENBUILD.2016.06.089.

[3] B.; Dean, J.; Dulac, K.; Petrichenko, P. Graham, Towards zero-emission efficient and resilient buildings - Global Status Report, APA, 2016. http://orbit.dtu.dk/files/127199228/GABC_Global_Status_Report_V09_november.pdf (accessed February 22, 2019).

[4] European Commision, The Energy Performance of Buildings Directive, 2018. https://ec.europa.eu/energy/sites/ener/files/documents/buildings_performance_factsheet.pdf (accessed March 8, 2019).

[5] Building Performance Institute Europe (BPIE), Europe's buildings under the microscope, A country-by-country review of the energy performance of buildings, Build. Perform. Inst. Eur. (2011). http://www.bpie.eu/uploads/lib/document/attachment/20/HR_EU_B_under_microscope_study.pdf (accessed March 27, 2015).

[6] Global Energy Assessment (GEA), Chapter 10 - Energy End-Use: Buildings, in: Build. Glob. Energy Assess. - Towar. a Sustain. Futur., 2012.

[7] J.A. Dirks, W.J. Gorrissen, J.H. Hathaway, D.C. Skorski, M.J. Scott, T.C. Pulsipher, M. Huang, Y. Liu, J.S. Rice, Impacts of climate change on energy consumption and peak demand in buildings: A detailed regional approach, Energy. 79 (2015) 20–32, https://doi.org/10.1016/J.ENERGY.2014.08.081.

[8] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (2008) 394–398, https://doi.org/10.1016/J.ENBUILD.2007.03.007.

[9] D. Connolly, H. Lund, B.V. Mathiesen, S. Werner, B. Möller, U. Persson, T. Boermans, D. Trier, P.A. Østergaard, S. Nielsen, Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system, Energy Policy. (2014), https://doi.org/10.1016/j.enpol.2013.10.035.

[10] I. Andrić, M. Koc, S.G. Al-Ghamdi, A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries, J. Clean. Prod. (2019), https://doi.org/10.1016/j.jclepro.2018.11.128.

[11] L. Kranzl, E. Aichinger, R. Büchele, S. Forthuber, M. Hartner, A. Müller, A. Toleikyte, Are scenarios of energy demand in the building stock in line with Paris targets?, Energy Effic. 12 (2019) 225–243, https://doi.org/10.1007/s12053-018-9701-1.

[12] H.M. Breunig, T. Huntington, L. Jin, A. Robinson, C.D. Scown, Dynamic Geospatial Modeling of the Building Stock To Project Urban Energy Demand, Environ. Sci. Technol. 52 (2018) 7604–7613, https://doi.org/10.1021/acs.est.8b00435.

[13] O. Kaynakli, A review of the economical and optimum thermal insulation thickness for building applications, Renew. Sustain. Energy Rev. 16 (2012) 415–425, https://doi.org/10.1016/J.RSER.2011.08.006.

[14] F. Ascione, N. Bianco, R.F. De Masi, F. de' Rossi, G.P. Vanoli, Energy refurbishment of existing buildings through the use of phase change materials: Energy savings and indoor comfort in the cooling season, Appl. Energy. 113 (2014) 990–1007. https://doi.org/10.1016/J.APENERGY.2013.08.045.

[15] P.H. Shaikh, N.B.M. Nor, P. Nallagownden, I. Elamvazuthi, T. Ibrahim, A review on optimized control systems for building energy and comfort management of smart sustainable buildings, Renew. Sustain. Energy Rev. 34 (2014) 409–429, https://doi.org/10.1016/J.RSER.2014.03.027.

[16] B. Zhou, W. Li, K.W. Chan, Y. Cao, Y. Kuang, X. Liu, X. Wang, Smart home energy management systems: Concept, configurations, and scheduling strategies, Renew. Sustain. Energy Rev. 61 (2016) 30–40, https://doi.org/10.1016/J.RSER.2016.03.047.

[17] R. Missaoui, H. Joumaa, S. Ploix, S. Bacha, Managing energy Smart Homes according to energy prices: Analysis of a Building Energy Management System, Energy Build. 71 (2014) 155–167, https://doi.org/10.1016/J.ENBUILD.2013.12.018.

[18] E. Merkel, R. McKenna, D. Fehrenbach, W. Fichtner, A model-based assessment of climate and energy targets for the German residential heat system, J. Clean. Prod. (2017), https://doi.org/10.1016/j.jclepro.2016.10.153.

[19] M. Hosseini, H. Akbari, Heating energy penalties of cool roofs: the effect of snow accumulation on roofs, Adv. Build. Energy Res. 8 (2014) 1–13, https://doi.org/10.1080/17512549.2014.890541.

[20] M. Olonscheck, A. Holsten, J.P. Kropp, Heating and cooling energy demand and related emissions of the German residential building stock under climate change, Energy Policy. 39 (2011) 4795–4806, https://doi.org/10.1016/J.ENPOL.2011.06.041.

[21] Housing, Energy and Thermal Comfort Housing, Energy and Thermal Comfort A review of 10 countries within the WHO European Region The WHO Regional Office for Europe, 2007. http://www.euro.who.int/pubrequest. (accessed March 8, 2019).

[22] R. Jevons, C. Carmichael, A. Crossley, A. Bone, Minimum indoor temperature threshold recommendations for English homes in winter – A systematic review, Public Health. 136 (2016) 4–12, https://doi.org/10.1016/J.PUHE.2016.02.007.

[23] Trafik- Bygge- og Boligstyrelsen, Bygningsreglementet, 2018. http://bygningsreglementet.dk/ (accessed February 7, 2019).

[24] ASHRAE, Standard 55 – Thermal Environmental Conditions for Human Occupancy, (2013). https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy (accessed March 8, 2019).

[25] IPCC, Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, Cambride University Press, Cambridge, United Kingdom and New York, NY, USA, 2014. https://doi.org/10.1017/CBO9781107415324.

[26] S. Rahmstorf, D. Coumou, Increase of extreme events in a warming world, Proc. Natl. Acad. Sci. U. S. A. 108 (2011) 17905–17909, https://doi.org/10.1073/pnas.1101766108.

[27] S.I. Seneviratne, M.G. Donat, B. Mueller, L.V. Alexander, No pause in the increase of hot temperature extremes, Nat. Clim. Chang. 4 (2014) 161–163, https://doi.org/10.1038/nclimate2145.

[28] V. V Kharin, F.W. Zwiers, · X Zhang, · M Wehner, X. Zhang, M. Wehner, Changes in temperature and precipitation extremes in the CMIP5 ensemble, Clim. Change. 119 (2013) 345–357. https://doi.org/10.1007/s10584-013-0705-8.

[29] J. Spinoni, J. Vogt, P. Barbosa, European degree-day climatologies and trends for the period 1951–2011, Int. J. Climatol. 35 (2015) 25–36, https://doi.org/10.1002/joc.3959.

[30] J. Spinoni, J. V. Vogt, P. Barbosa, A. Dosio, N. McCormick, A. Bigano, H.M. Füssel, Changes of heating and cooling degree-days in Europe from 1981 to 2100, Int. J. Climatol. 38 (2018) e191–e208. https://doi.org/10.1002/joc.5362

[31] G. Pagliarini, C. Bonfiglio, P. Vocale, Outdoor temperature sensitivity of electricity consumption for space heating and cooling: An application to the city of Milan, North of Italy, Energy Build. 204 (2019) 109512, https://doi.org/10.1016/j.enbuild.2019.109512.

[32] M.E. Angeles, J.E. González, N. Ramírez, Impacts of climate change on building energy demands in the intra-Americas region, Theor. Appl. Climatol. 133 (2018) 59–72, https://doi.org/10.1007/s00704-017-2175-9.

[33] M. De Rosa, V. Bianco, F. Scarpa, L.A. Tagliafico, Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach, Appl. Energy. 128 (2014) 217–229, https://doi.org/10.1016/J.APENERGY.2014.04.067.

[34] S. Petrovic, K. Karlsson, Model for Determining Geographical Distribution of Heat Saving Potentials in Danish Building Stock, ISPRS Int. J. Geo-Information. 3 (2014) 143–165, https://doi.org/10.3390/ijgi3010143.

[35] V.M. Nik, A. Sasic Kalagasidis, Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties, Build. Environ. 60 (2013) 291–304, https://doi.org/10.1016/J.BUILDENV.2012.11.005.

[36] F. Giorgi, W.J. Gutowski, Regional Dynamical Downscaling and the CORDEX Initiative, Annu. Rev. Environ. Resour. 40 (2015) 467–490, https://doi.org/10.1146/annurev-environ-102014-021217.

[37] L. Crhová, E. Holtanová, Simulated relationship between air temperature and precipitation over Europe: sensitivity to the choice of RCM and GCM, Int. J. Climatol. 38 (2018) 1595–1604, https://doi.org/10.1002/joc.5256.

[38] E.J. Kendon, R.G. Jones, E. Kjellström, J.M. Murphy, Using and Designing GCM–RCM Ensemble Regional Climate Projections, J. Clim. 23 (2010) 6485–6503, https://doi.org/10.1175/2010JCLI3502.1.

[39] L.R. Møller, M. Drews, M.A.D. Larsen, Simulation of Optimal Decision-Making Under the Impacts of Climate Change, Environ. Manage. (2017), https://doi.org/10.1007/s00267-017-0852-1.

[40] K. Halsnæs, M.A.D. Larsen, P.S. Kaspersen, Climate change risks for severe storms in developing countries in the context of poverty and inequality in Cambodia, Nat. Hazards. 94 (2018) 261–278, https://doi.org/10.1007/s11069-018-3387-8.

[41] A. Dosio, R.G. Jones, C. Jack, C. Lennard, G. Nikulin, B. Hewitson, What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models, Clim. Dyn. 53 (2019) 5833–5858, https://doi.org/10.1007/s00382-019-04900-3.

[42] The European Forum for GeoStatistics, GEOSTAT 1A-Representing Census data in a European population grid Final Report, 2012.

[43] Eurostat, GEOSTAT - Eurostat, Geostat. (2016). https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/population-distribution-demography/geostat (accessed February 7, 2019).

[44] Enerdata - ODYSSEE, The EU database on energy efficiency data & indicators, (n.d.). https://odyssee.enerdata.net/home/ (accessed June 15, 2020).
[45] D. Matte, M.A.D. Larsen, O.B. Christensen, J.H. Christensen, Robustness and scalability of regional climate projections over Europe, Front. Environ. Sci. 6 (2019) 163, https://doi.org/10.3389/FENVS.2018.00163.
[46] J.H. Christensen, M.A.D. Larsen, O.B. Christensen, M. Drews, M. Stendel, Robustness of European climate projections from dynamical downscaling, Clim. Dyn. (2019), https://doi.org/10.1007/s00382-019-04831-z.
[47] A. Dosio, Projections of climate change indices of temperature and precipitation from an ensemble of bias-adjusted high-resolution EURO-CORDEX regional climate models, J. Geophys. Res. Atmos. 121 (2016) 5488–5511, https://doi.org/10.1002/2015JD024411.
[48] M.A.D. Larsen, S. Petrovic, R.E. Engström, M. Drews, S. Liersch, K.B. Karlsson, M. Howells, Challenges of data availability: Analysing the water-energy nexus in electricity generation, Energy Strateg. Rev. 26 (2019), https://doi.org/10.1016/j.esr.2019.100426 100426.
[49] H. Wang, Q. Chen, Impact of climate change heating and cooling energy use in buildings in the United States, Energy Build. 82 (2014) 428–436, https://doi.org/10.1016/j.enbuild.2014.07.034.
[50] A. Dodoo, L. Gustavsson, F. Bonakdar, Effects of Future Climate Change Scenarios on Overheating Risk and Primary Energy Use for Swedish Residential Buildings, Energy Procedia. 61 (2014) 1179–1182, https://doi.org/10.1016/j.egypro.2014.11.1048.
[51] S. Sorrell, J. Dimitropoulos, M. Sommerville, Empirical estimates of the direct rebound effect: A review, Energy Policy. 37 (2009) 1356–1371, https://doi.org/10.1016/j.enpol.2008.11.026.
[52] R. McKenna, L. Hofmann, E. Merkel, W. Fichtner, N. Strachan, Analysing socioeconomic diversity and scaling effects on residential electricity load profiles in the context of low carbon technology uptake, Energy Policy. (2016), https://doi.org/10.1016/j.enpol.2016.06.042.
[53] N.J. Kelly, J. Cockroft, Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data, Energy Build. 43 (2011) 239–245, https://doi.org/10.1016/j.enbuild.2010.09.018.
[54] O. Balyk, K.S. Andersen, S. Dockweiler, M. Gargiulo, K. Karlsson, R. Næraa, S. Petrović, J. Tattini, L.B. Termansen, G. Venturini, TIMES-DK: Technology-rich multi-sectoral optimisation model of the Danish energy system, Energy Strateg. Rev. 23 (2019) 13–22, https://doi.org/10.1016/j.esr.2018.11.003.
[55] R. McKenna, E. Merkel, D. Fehrenbach, S. Mehne, W. Fichtner, Energy efficiency in the German residential sector: A bottom-up building-stock-model-based analysis in the context of energy-political targets, Build. Environ. (2013), https://doi.org/10.1016/j.buildenv.2013.01.002.
[56] K. Gram-Hanssen, Efficient technologies or user behaviour, which is the more important when reducing households' energy consumption?, Energy Effic. 6 (2013) 447–457, https://doi.org/10.1007/s12053-012-9184-4.
[57] S. Batel, P. Devine-Wright, T. Tangeland, Social acceptance of low carbon energy and associated infrastructures: A critical discussion, Energy Policy. (2013), https://doi.org/10.1016/j.enpol.2013.03.018.
[58] B.P. Koirala, E. Koliou, J. Friege, R.A. Hakvoort, P.M. Herder, Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems, Renew. Sustain. Energy Rev. (2016), https://doi.org/10.1016/j.rser.2015.11.080.
[59] K. Schumacher, F. Krones, R. McKenna, F. Schultmann, Public acceptance of renewable energies and energy autonomy: A comparative study in the French, German and Swiss Upper Rhine region, Energy Policy. (2019), https://doi.org/10.1016/j.enpol.2018.11.032.
[60] T. Boermans, J. Grözinger, B. Von Manteuffel, N. Surmeli-Anac, A. John, K. Leutgöb, D. Bachner, Assessment of cost optimal calculations in the context of the EPBD (ENER/C3/2013-414) Final report, 2015. www.ecofys.com (accessed October 23, 2019).
[61] J. Zuo, Z.Y. Zhao, Green building research-current status and future agenda: A review, Renew. Sustain. Energy Rev. (2014), https://doi.org/10.1016/j.rser.2013.10.021.
[62] F. Berg, M. Fuglseth, Life cycle assessment and historic buildings: Energy-efficiency refurbishment versus new construction in Norway, J. Archit. Conserv. (2018), https://doi.org/10.1080/13556207.2018.1493664.
[63] B. Zhou, D. Rybski, J.P. Kropp, The role of city size and urban form in the surface urban heat island, Sci. Rep. 7 (2017) 1–9, https://doi.org/10.1038/s41598-017-04242-2.