Changes of heating and cooling degree-days in Europe from 1981 to 2100

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ABSTRACT: During the last decades, the effects of global warming have become apparent also in Europe, causing relevant impacts in many sectors. Under projected future global warming, such a tendency can be expected to persist until the end of this century and beyond. Identifying which climate-related impacts are likely to increase, and by how much, is an important element of any effective strategy for managing future climate risks. This study investigates whether energy demand for cooling and heating buildings can be expected to increase or decrease under climate change. Two indicators of weather-related energy consumption for heating and cooling buildings are considered: heating degree-days (HDD) and cooling degree-days (CDD). The evolution of these indicators has been analysed based on 11 high-resolution bias-adjusted EURO-CORDEX simulations for two emission representative concentration pathways (RCP4.5 and RCP8.5). Both indicators have been validated over the period 1981–2010 using an independent dataset that contains more than 4000 station data, showing very high correlation over most of Europe. Trends of HDD and CDD from 1981 to 2100, together with their uncertainties, are analysed. For both RCPs, all simulations project a significant decrease for HDD, especially over Scandinavia and European Russia, and an increase of CDD which peaks over the Mediterranean region and the Balkans. Overall, degree-day trends do not show remarkable differences if population weighting is applied. If a constant population scenario is considered, the decrease in HDD will outbalance the increase in CDD in the 21st century over most of Europe. Thus the related energy demand (expressed as Energy Degree-days, EDD) is expected to decrease. If, however, population projections over the 21st century are included in the calculations, it is shown that despite the persisting warming, EDD will increase over northern Europe, the Baltic countries, Great Britain, Ireland, Benelux, the Alps, Spain, and Cyprus, resulting in an overall increase in EDD over Europe.

KEY WORDS climate change; degree-days; energy demand; Europe; CORDEX; population weighting

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1. Introduction

The last decades of the 20th century and the beginning of the 21st century have witnessed a global rise in temperatures and a higher frequency of extreme climate events (IPCC, 2014a). Climate change fosters natural disasters (Helmer and Hilhorst, 2006) and Europe is experiencing more frequent and severe meteorological and streamflow droughts, heat and cold waves, river and coastal flooding, wildfires, and windstorms (Lindner et al., 2014; Russo et al., 2014; Spinoni et al., 2015a, 2015b; Aponte et al., 2016; Forzieri et al., 2016). These events have a wide range of economic, social, and environmental impacts, making it difficult to coordinate adaptation strategies across Europe (Biesbroek et al., 2010; Iglesias et al., 2012). Sectors affected by climate-related impacts include agriculture (Bindi and Olesen, 2011; Vermeulen et al., 2012), forest ecosystems (Lindner et al., 2010), and energy consumption (Santamouris et al., 2015). These impacts are expected to become stronger in the future (Bellard et al., 2012; Calzadilla et al., 2013; Lindner et al., 2014; Harrison et al., 2015) due to the projected global warming over Europe (Jacob et al., 2014; IPCC, 2014a). It is therefore essential to understand the extent to which crucial sectors, such as energy demand, will potentially be affected by the evolution of climate in the next decades. The expected rise in global temperature is likely to increase the energy needed to cool buildings in the summer, and to decrease the energy needed to heat the buildings in the winter. To estimate the weather-related impacts on the net energy demand for buildings, two indicators are commonly used: heating degree-days (HDD) (e.g. Thom, 1954; Quayle and Díaz, 1980) and cooling degree-days (CDD) (e.g. Thom, 1959; De Rosa et al., 2014). HDD (derived over winter months) and CDD (derived over summer months) are both computed based on the cumulated...
daily deviations below (for HDD) or above (for CDD) a given temperature threshold (i.e. the base temperature) that varies according to the indicator, region, and scope of the analysis (Schoenau and Kehrig, 1990). Although the use of degree-days presents some limitations (McIntyre et al., 1987; Day and Karayiannis, 1999; Bonhomme, 2000; Moral-Carcedo and Vicens-Otero, 2005; Antunes Azevedo et al., 2015), they are widely applied for climatological and impact analyses, both in Europe (Büyükalaca et al., 2001; Matzarakis and Balafoutis, 2004; Ortiz-Beviá et al., 2012; Spinoni et al., 2015c) and other regions (e.g. Wang et al., 2010; Castañeda and Claus, 2013; Wang and Chen, 2014; Petri and Caldeira, 2015; Shi et al., 2016).

This study builds on an earlier study by Spinoni et al. (2015c), where the temporal evolution of HDD and CDD in Europe during 1950–2012 was analysed. In particular, that study showed a general increase of CDD and a converse decrease in HDD, both of which are more significant from the early 1980s onwards. Although the respective increase and decrease generally followed the corresponding temperature trends and noticeably depended on latitude, that study also accounted for the spatial patterns over Europe, which may be a key factor for regional impacts, as reported for different countries (e.g. Christenson et al., 2006; Yildiz and Sosaoglu, 2007; Semmler et al., 2010; De Rosa et al., 2015; Cvitan and Sokol Jurković, 2016).

Recent studies have addressed the projection of degree-days for different global regions (You et al., 2014; Erhardt, 2015). In Europe, such studies have usually focused on the length of the growing season (Rustenjoja et al., 2016) and especially concerning grapevines (Moriondo et al., 2013; Fraga et al., 2015). To the best of our knowledge, to date there have been no published studies about future tendencies of HDD and CDD over the entire European continent.

In the present study, we investigate the likely evolution of HDD and CDD until the end of the 21st century, with the twofold aim of analysing the climatological aspects and providing the stakeholders and decision-makers with information in support of the management of future climate impacts on European energy markets. The latter may also be useful for planning mitigation or adaptation strategies. Specifically, the study analyses the spatial distribution and magnitudes of the likely significant trends in HDD and CDD from 1981 to 2100. The input data for the study were generated by regional climate models (RCMs) participating in the EURO-CORDEX initiative (coordinated regional downscaling experiment) (Jacob et al., 2014). HDD and CDD values were computed directly from projected bias-adjusted daily minimum ($T_N$) and maximum ($T_X$) temperatures of 11 simulations (Dosio, 2016), and under two scenarios based on two representative concentration pathways, namely RCP4.5 and RCP8.5 (IPCC, 2014a, 2014b).

In Section 2, an overview of the EURO-CORDEX data is presented, the equations to compute the degree-day variables are described, and the population weighting applied to HDD and CDD is explained. In Section 3, the validation of the results for the period 1981–2010 is described, and the climatologies and trend maps of HDD and CDD for two emission scenarios from 1981 to 2100, as well as the uncertainty related to the trend values, are presented. The possible impacts on energy demand of the projected population increase (or decrease) per country, in light of the combined evolution of HDD and CDD over the 21st century, are also considered in Section 3. Finally, in Section 4, the outcomes of the study are discussed and planned further activities on this topic are outlined.

2. Data and methods

2.1. Input data: bias-adjusted EURO-CORDEX simulations

RCPs refer to four scenarios (or trajectories) of greenhouse gas (GHG) atmospheric concentrations until the year 2100, which were adopted by the IPCC in its Fifth Assessment Report (IPCC, 2014a, 2014b). The four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) are named after the possible range of ‘radiative forcing’ values at the end of the 21st century, relative to pre-industrial values: +2.6, +4.5, +6.0, and +8.5 W m$^{-2}$ (Meinshausen et al., 2011; Van Vuuren et al., 2011). For the purposes of this study we selected two RCPs: the moderate RCP4.5 and the more extreme RCP8.5. Under RCP4.5, GHG emissions will peak around the early 2050s and then stabilize, causing a CO$_2$ equivalent of about 650 ppm (parts per million) and a temperature increase of approximately 1.8–2.0°C in 2100, compared to the control period of 1986–2005 (Moss et al., 2010; Thomson et al., 2011). RCP8.5, on the other hand, predicts a continuous rise of GHG emissions until 2100, causing a CO$_2$ equivalent larger than 1370 ppm and a temperature increase close to 4°C (Riahi et al., 2007; Moss et al., 2010; Riahi et al., 2011; Van Vuuren et al., 2011; IPCC, 2014b).

The results of the EURO-CORDEX simulations (http://www.euro-cordex.net) have been used as input data for our study. The main features and results of EURO-CORDEX are described by Vautard et al. (2013), Jacob et al. (2014), and Kotlarski et al. (2014). Of the two available subsets (i.e. EUR-44 and EUR-11) of EURO-CORDEX simulations, we selected EUR-11, characterized by a finer resolution of 0.11° (~12.5 km). From the complete set of available simulations, only the 11 bias-adjusted ones were used (Dosio, 2016). For the bias-adjustment, the E-OBS high-resolution gridded data set of daily climate over Europe (E-OBS version 10, released in April 2014; Haylock et al., 2008) has been used as a reference data set for the period 1981–2010. The use of bias-adjusted input data is very useful to avoid unreliable spatial patterns (Tebaldi and Knutti, 2007; Christensen et al., 2008; Katragkou et al., 2015). The bias-adjustment methodology used in this study was originally developed by Piani et al. (2010), and has been applied to the FP6 project ENSEMBLES simulations by Dosio and Paruolo (2011) and Dosio et al. (2012).

Table 1 shows the details of the climate change simulations used in our analyses. As can be seen, they are based on five different regional circulation models (RCMs)
and five global circulation models (GCMs). At the time of bias-adjustment (Dosio, 2016), the selected simulations were the only 11 EURO-CORDEX model runs available, and consequently they cannot capture all of the variability of the CMIP5 (Coupled Model Intercomparison Project Phase 5) suite of climate simulations. However, although not directly comparable, the results for the projection of climate change indices from the EURO-CORDEX bias-adjusted simulations (Dosio, 2016) are in line with those shown by Stillmann et al. (2013) over Europe. More details on the complete set of simulations, models, and participants related to EURO-CORDEX are available at http://www.euro-cordex.net/.

In this study, the degree-days (heating and cooling) for the period 1981–20100 were computed (as described below) based on daily values of minimum and maximum temperature. Note that the RCP4.5 and the RCP8.5 data refer to the years 2006–2100, while historical data for the years 1981–2005 have been added to both scenarios. Quality checks and homogenization tests of the input daily temperature data have been performed using the MASH software (Szentimrey, 1999; Szentimrey, 2011). While not normally necessary for data from climate simulations, these checks were made because the bias-adjustment procedure could potentially lead to inhomogeneities especially over regions with complex topography. For each simulation and scenario, whenever a daily temperature value failed a statistical test, it was replaced by interpolating the eight spatially closest values. When this was not possible, the closest values in time were used, up to 10 days before and after. A few values which could not be replaced were discarded. For a given month, if more than three values were discarded, that month was not used to obtain degree-days. Considering all of the simulations, this occurred for less than 0.2% of the grid points, and only in sparse areas in Scandinavia and Russia, especially regarding summer minimum temperatures. Once quality checking was complete, mean temperature was computed by averaging minimum and maximum temperature values for each single day, grid point, and simulation.

Finally, it should be noted that the area of interest for this study is the EURO-CORDEX domain excluding African and Middle-East territories, as well as central Turkey, because of the low availability of data used during the bias-adjustment.

### 2.2. Degree-day variables: equations and baselines

Variables based on degree-days are frequently used to assess the economic and environmental impacts of climate change. HDD and CDD are widely used indicators of energy consumption for heating and cooling buildings (CIBSE, 2006), while growing degree-days (GDD) are important indicators of accumulated heat, which are used, for example, to predict the phenology and harvesting of agricultural crops (McMaster and Wilhelm, 1997). In general, GDD have been more frequently applied than HDD and CDD, especially in agro-climatic studies related to a wide variety of crops (Moriondo and Bindi, 2007; Qian et al., 2010; Kenealy et al., 2013; Asseng et al., 2014; Zhang et al., 2016). GDD are also commonly used in other fields, such as forestry (Ruosch et al., 2015), vegetation conditions (Miller et al., 2001; Graham et al., 2014), and pest management (Pruss, 1983). In more recent years, however, many studies have focussed on the use of HDD and CDD to estimate annual and seasonal trends in the energy demand for heating and cooling residential, commercial, and industrial buildings, especially in the context of climate change (Hadley et al., 2006; Yildiz and Sosaoglu, 2007; Morna and van Vuuren, 2009; Wang et al., 2010; Zhao and Magoulès, 2012; Auffhammer and Mansur, 2014; Wang and Chen, 2014; Labriet et al., 2015; Shi et al., 2016).

HDD reflect the amount of energy needed (e.g. by a building heating system), for a given day or period, to heat the internal environment in a cold climate to a specified base temperature (e.g. 15.5°C), while CDD reflect the amount of energy needed (e.g. by a building cooling system), for a given day or period, to cool the internal environment in a hot climate to a specified base temperature (e.g. 22°C). The theoretical formulation of heating and cooling (and growing) degree-days can be performed in different ways, depending on the nature and scope of the study (Thom, 1954; Schoenau and Kehrig, 1990). Computation methods range from simple models based on monthly or

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**Table 1. Bias-adjusted EURO-CORDEX simulations used in this study.**

| GCM                  | RCM             | GCM members | Data period | Contributor |
|----------------------|-----------------|-------------|-------------|-------------|
| CNRM-CM5-LR          | CCLM4-8-17      | r1i1p1      | 1981–2100   | CLMcom      |
| EC-EARTH             | r1i1p1          |             |             |             |
| MPI-ESM-LR           | r1i1p1          |             |             |             |
| EC-EARTH             | HIRAM5          | r1i1p1      | 1981–2100   | DMI         |
| IPSL-CM5A-LR         | WRF331F         | r1i1p1      | 1981–2100   | IPSL/HadGEM |
| EC-EARTH             | RCA022E         | r1i1p1      | 1981–2100   | KNMI        |
| CNRM-CM5-LR          | RCA4            | r1i1p1      |             | SMHI        |
| EC-EARTH             | r1i1p1          |             |             |             |
| IPSL-CM5A-MR         | r1i1p1          |             |             |             |
| HadGem2-ES           |                 |             | 1981–2098   |             |
| MPI-ESM-LR           |                 |             | 1981–2100   |             |

For the complete list of the acronyms, see http://www.euro-cordex.net/060376/index.php.en and http://www.euro-cordex.net/060379/index.php.en.
annual temperature (McMaster and Wilhelm, 1997; Mourshed, 2012; Yin et al., 2017) to more sophisticated parameterizations (Allen, 1976; Gelegenis, 2009).

In this study, HDD and CDD were computed using the same method that was used in the earlier study by Spinoni et al. (2015c) on European degree-day climatologies and trends during recent decades, as well as in a major study of global warming impacts on residential heating and cooling demand in the United States (Petri and Caldeira, 2015). Using this method, which was developed by the UK Met Office in 1928 (CIBSE, 2006), daily HDD and CDD are calculated based on a comparison of daily minimum and maximum air temperatures with the selected base temperature, taking account of fluctuations of daily air temperature around the base temperature, as well as the asymmetry between daily average temperature and diurnal temperature variations. The UK Met Office equations for computing daily HDD and CDD are shown in Tables 2 and 3.

In this study daily HDD values are computed using a base temperature of 15.5 °C, while daily CDD values are computed using a base temperature of 22 °C. Other base temperatures which are used to compute HDD and CDD, both in Europe and elsewhere, are described in Spinoni et al. (2015c). Annual HDD values were computed as the cumulated sum of daily HDD values for the ‘heating season’, defined as the 6-month period from 1 October to 31 March. Annual CDD values were computed as the cumulated sum of daily CDD values for the ‘cooling season’, defined as the 6-month period from 1 April to 30 September. It should be noted that while the heating season can last longer in northern Europe than in southern Europe, we decided to keep the same 6-month period for all of Europe, in order to produce maps that are spatially homogeneous, and to avoid an artificial zonation, also possibly based on national laws on heating.

Finally, for every grid point in the study area and for each RCP scenario, we obtained annual time series of HDD and CDD for the period 1981–2100, for each of the 11 simulations listed in Table 1. These time series were further processed to remove possible outliers and suspect data, by means of statistical tests based on the Peirce’s criterion (Ross, 2003). Any value that failed one of the tests was removed from the series without being replaced. Because of the overall high quality of input data, very few values (i.e. less than 0.05%) of sparse grid points were removed, which decreases even further (i.e. less than 0.01%) if we exclude the northern part of Fennoscandia and northern Russia.

2.3. Trend analysis, population weighting, and population projections

For the annual HDD and CDD time series which passed the quality tests, a linear trend analysis was performed over the entire period. Given that the RCP4.5 scenario predicts a slowdown or even a stabilization of temperature rise after the middle of the 21st century (IPCC, 2014a), we also evaluated the use of bi-modal trends. However, considering that the RCP8.5 scenario projects a continuous temperature rise from the period 1981–2010 until the end of this century (IPCC, 2014a), in the end the linear model was selected in order to make the results comparable. For each projected degree-day variable, we also derived difference maps, computed as the difference between the ‘near-future’ (i.e. 2041–2070) and the ‘recent past’ (i.e. 1981–2010), and between the ‘far-future’ (i.e. 2071–2100) and the ‘recent past’. Furthermore, in addition to the ensemble mean of the trends and anomalies, we also computed the standard error of the trend values, in order to provide a measure of the uncertainty. In this study, the standard error of the ensemble mean of the trends corresponds to the average of the single standard errors of the trend values provided by the 11 simulations, which have been calculated using the ordinary least squares (OLS) method applied to linear regression (Wilks, 2011). To achieve this, we assumed independence across

| Case | Condition | HDD |
|------|-----------|-----|
| 1    | $T_{\text{max}} \leq T_{\text{base}}$ (i.e. uniformly cold day) | HDD = $T_{\text{base}} - T_{\text{avg}}$ |
| 2    | $T_{\text{avg}} \leq T_{\text{base}} < T_{\text{max}}$ (i.e. mostly cold day) | HDD = $[T_{\text{base}} - T_{\text{min}}]/2 - [T_{\text{max}} - T_{\text{base}}]/4$ |
| 3    | $T_{\text{min}} < T_{\text{base}} < T_{\text{avg}}$ (i.e. mostly warm day) | HDD = $(T_{\text{base}} - T_{\text{min}})/4$ |
| 4    | $T_{\text{min}} \geq T_{\text{base}}$ (i.e. uniformly warm day) | No heating is required, so HDD = 0 |

Daily average temperature ($T_{\text{avg}}$) is calculated as $(T_{\text{max}} + T_{\text{min}})/2$. For this study, $T_{\text{base}}$ was set to 15.5 °C.

| Case | Condition | CDD |
|------|-----------|-----|
| 1    | $T_{\text{max}} \leq T_{\text{base}}$ (i.e. uniformly cold day) | No cooling is required so CDD = 0 |
| 2    | $T_{\text{avg}} \leq T_{\text{base}} < T_{\text{max}}$ (i.e. mostly cold day) | CDD = $(T_{\text{max}} - T_{\text{base}})/4$ |
| 3    | $T_{\text{min}} < T_{\text{base}} < T_{\text{avg}}$ (i.e. mostly warm day) | CDD = $[T_{\text{max}} - T_{\text{base}}]/2 - [T_{\text{base}} - T_{\text{min}}]/4$ |
| 4    | $T_{\text{min}} \geq T_{\text{base}}$ (i.e. uniformly warm day) | CDD = $T_{\text{avg}} - T_{\text{base}}$ |

Daily average temperature ($T_{\text{avg}}$) is calculated as $(T_{\text{max}} + T_{\text{min}})/2$. For this study, $T_{\text{base}}$ was set to 22 °C.
the 11 modelling runs. However, this major assumption cannot be completely true, because the simulations used in this study share the GCM or RCM (Table 1). The analysis was performed at grid-point scale, but also aggregated at macro-regional and continental scale. In the latter cases, the standard error derives from the average of the standard errors over the grid points for the investigated region.

In order to investigate whether the expected decrease in HDD and increase in CDD are likely to cause a corresponding decrease in energy demand, we incorporated data on population in the analyses. The combined use of population data and degree-day variables is not new in the scientific literature (Taylor, 1981; Guttmann, 1983). However, this approach has been more frequently used in recent years, for example in studies in the United States (Albouy et al., 2013; Zhou et al., 2014), China (Shi et al., 2016), and Europe (Fantini and Schenone, 2001; European Environment Agency (EEA), 2012; Ortiz-Beviá et al., 2012). Most of these studies employed population weighting at sub-national level, in order to capture more effectively important differences between HDD or CDD changes for densely or sparsely populated areas, while also taking account of different population projections for regions with different population levels. However, our analysis may be seen as a new, experimental approach in so far as it is focussed on degree-day trends induced by climate change, rather than an investigation of the socio-economic impacts and implications of population-related degree-day increases. The application of our degree-day analysis of future trends paves the way for a broader approach, including the use of population scenarios that are consistent with the new shared socio-economic pathways (SSPs) (Jones and O’Neill, 2016).

The first population data used were the high-resolution (i.e. approximately 1 km$^2$) GEOSTAT 2011 population-grid data sets (GEOSTAT, 2012), produced jointly by Eurostat and the European Forum for Geography and Statistics as part of the GEOSTAT 1 project (http://www.efgs.info/geostat/). Because the GEOSTAT 2011 data sets are only available for the EU-28 countries (plus Iceland, Norway, and Switzerland), the following countries were excluded from this part of the analysis: Bosnia and Herzegovina, Serbia, Macedonia, Montenegro, Albania, Belarus, Ukraine, Moldova, and Russia. Because no degree-day quantities were computed over Malta, it was also excluded. Following the re-scaling of the GEOSTAT 2011 population data to the EURO-CORDEX spatial resolution (i.e. 0.11°), a simple population-weighting scheme was applied to the HDD and CDD annual time series for 1981–2100, using population data of 2011 and assuming no population changes during the 21st century. The results are population-weighted degree-day trends for 1981–2100, at country, macro-regional, and continental scale.

As a further separate step, in order to take account of possible demographic changes during the 21st century, we introduced projected population data provided by Eurostat (Eurostat, 2014), and available at country scale for the EU-28 countries plus Iceland, Norway, and Switzerland. These probabilistic projections are based on many assumptions regarding current trends in population change, likely future size and structure of the population, age-specific fertility and mortality rates, life expectancy by age and sex, as well as international net migration by age and sex. Details on the projections are provided by Scherbov et al. (2008) and the European Commission (2015). The data on demography, at national and at regional level, are collected by Eurostat from the national statistical institutes of all EU Member States and most non-EU countries in Europe. Unfortunately, however, no information about uncertainty of the data is contained in the Eurostat population projections metadata, and so it was not possible to combine the uncertainty of HDD and CDD trends with that of the population data. Therefore, while the importance of uncertainty of population projections is well documented (Lutz and Goldstein, 2004; Lutz et al., 2008; Wilson, 2013), the population-weighted degree-day projections that are presented here only consider uncertainty of the degree-day quantities.

The population data and projections of Eurostat which were used for this part of the study refer to the years 2010, 2050, and 2080. Therefore, for each country the population-weighted HDD and CDD were first averaged for the corresponding 10-year periods (i.e. 2005–2015, 2045–2055, and 2075–2085), the three values were then scaled (multiplied) using that country’s population data for 2010, 2050, and 2080, and the differences (as a percentage) versus 2010 were computed. To ensure comparable results, we computed the same differences between 2050 and 2010 and between 2080 and 2010, using population-weighted degree-days combined with constant (i.e. 2011) and projected population data, in order to estimate how important the change in population could be for heating and cooling energy demand.

3. Results and discussion

3.1. Pre-validation: comparisons with independent data sources

As a pre-validation exercise, the degree-day quantities derived from the EURO-CORDEX simulations for the period 1981–2010 were compared with those derived from an independent data set of meteorological observations [described in Spinoni et al. (2015c)], which comprises 4012 reconstructed and homogenized monthly records of minimum, mean, and maximum temperature, for the period 1951–2011. These weather station data sets were developed by combining data from three separate sources: the monitoring agricultural resources (MARS) agro-meteorological database (http://agri4cast.jrc.ec.europa.eu/) hosted by the Joint Research Centre (JRC) of the European Commission; the global historical climatology network-monthly (GHCN-M) temperature data set, available from the National Centres for Environmental Information (NCEI) of National Oceanic and Atmospheric Administration (NOAA) in the United States.
(Menne et al., 2012); and the European climate and assessment dataset (ECA&D) meteorological database of Royal Netherlands Meteorological Institute (KNMI) (Klein Tank et al., 2002). It should be noted that although the ECA&D database is used to create and update the E-OBS gridded climate data set, any auto-correlation effects will be minimal, because the ECA&D database represents less than 15% of data.

Average annual HDD and CDD values for 1981–2010 were derived by applying the UK Met Office equations (Tables 2 and 3) to the monthly records for each weather station. The degree-day values were then spatially interpolated over the same grid used by the EURO-CORDEX simulations, by means of the kriging with external drift (KED) method, using elevation as external drift (Hengl, 2009). The resulting HDD and CDD time series were then compared with the corresponding annual HDD and CDD averaged over 1981–2010 and computed as the ensemble mean of the simulations used in this study. To avoid methodological bias, the UK Met Office equations were also applied to the monthly EURO-CORDEX temperature data.

Figure 1 shows the differences in spatial distributions of HDD and CDD based on EURO-CORDEX simulations and interpolated weather station data. As can be seen, the EURO-CORDEX simulations slightly overestimate HDD (by approximately 0.7% over the whole of Europe), with annual HDD values ranging from 50 to 120 over most of Europe. However, overestimation of HDD is greater than 3% only in southern Spain, where it peaks at 230 (due to the extended greenhouse environment around Almeria), and over the Alpine border between France and Italy, where it peaks at about 120 over Haute-Savoie. In contrast, the underestimation of HDD is greatest (∼40) over the mountain glaciers in Iceland. For CDD, no remarkable differences are evident, except over southern Spain and northern Italy, where they are slightly greater than 5% (up to 80 in the area around Almeria). In summary, the use of a homogenized historical data set as a reference for validation, and the few divergent spatial patterns, suggest that the use of bias-adjusted EURO-CORDEX simulations is likely to lead to a robust analysis of degree-day climatologies and trends.

3.2. Spatial comparisons of HDD and CDD: recent past versus near and far future

Before analysing the trends of the projected HDD and CDD from 1981 to 2100, an assessment was made of the spatial distributions of the HDD and CDD values for the three time horizons of interest: the ‘recent past’, the ‘near future’, and the ‘far future’. Figure 2 shows the ensemble average annual HDD and CDD values for the recent past (i.e. 1981–2010). Figure 3 shows the deviation from the recent past of average annual HDD and CDD for the near future (i.e. 2041–2070), while Figure 4 shows the deviation from the recent past of average annual HDD and CDD for the far future (i.e. 2071–2100). Note that the differences (decreases or increases) in degree-day quantities are shown in Figures 3 and 4 as absolute values, for two main reasons. Firstly, although there is no simple equation linking energy demand and degree-days, nonetheless the energy needed to heat (or cool) the internal environment could be approximately inferred from HDD (or CDD) values, and so, by only showing relative differences, this information would be lost for users. Secondly, due to small or very small absolute CDD values over latitudes above 50°N, maps and colour scales could be distorted by extremely large percentage increases of CDD in those regions.

Regarding the spatial distribution of degree-days in the recent past (Figure 2), for both HDD and CDD there are clear patterns related to latitude and elevation, while in the case of HDD there is also a smooth increase from southwest to northeast. In general, latitudinal gradients dominate above 50°N, whereas elevation gradients are most evident in central Europe, and even more in the Mediterranean region, which shows the smallest HDD values (often less than 1200 in coastal areas) and the largest CDD values (greater than 500 in southern Spain and the areas bordering the Aegean Sea).

Comparing the differences in degree-days between the recent past and the near future (Figure 3), it can be seen that Europe is projected to see a decrease in HDD, which is larger under RCP8.5 than under RCP4.5, as expected. In absolute values, the decrease in HDD is largest over northeastern Europe, with values between −800 and −1000, and smallest in southwestern Europe, where the decrease in HDD over the Mediterranean region is (on average) about −200 under RCP4.5 and −300 under RCP8.5. However, in percentage values, the decrease in HDD is largest in southern Europe, where values are projected to fall (on average) by 30% under RCP4.5 and 35% under RCP8.5. In summary, in the near future northern Europe is projected to see a reduction in HDD, ranging from −17 to −23% under RCP4.5, and −21 to −28% under RCP8.5. Central Europe, on the other hand, shows more homogeneous spatial patterns, and the reduction in HDD is (on average) about −18% under RCP4.5 and −22% under RCP8.5.

On the other hand, Figure 3 shows that the projected increase in CDD in the near future is not much different under RCP4.5 and RCP8.5, except over the Mediterranean region where it is larger under RCP8.5. In absolute values, the increase in CDD is generally much smaller than the converse decrease in HDD, which is due to the definition of HDD and CDD, and also because of the base temperatures chosen in this study (see Section 2.2). However, in percentage values, this situation is reversed for Spain, southern Italy, Greece, and Turkey, where the projected increase in CDD is greater than 40%, in particular under RCP8.5.

Comparing the differences in degree-days between the recent past and the far future (Figure 4), it can be seen that both the RCP4.5 and RCP8.5 scenarios project a continuous decrease in HDD until the end of the 21st century, even though RCP4.5 assumes a stabilization of CO₂ equivalent after the early 2050s. The HDD values projected by the more moderate RCP4.5 for the far future are similar to those projected by the more extreme RCP8.5.
for the near future. In absolute values, the RCP8.5 scenario projects a decrease of HDD of more than −800 for most of Europe, and of more than −1100 for large parts of northeastern Europe. In percentage values, under RCP8.5, the decrease in HDD ranges from −60 to −50% over southern Europe, and −35 to −45% over northern Europe. This change is expected to cause a significant reduction in energy demand. In summary, comparing projected HDD for the far future with that of the recent past, we can roughly identify a southwest to northeast gradient, from Lisbon to the Urals, of −1 HDD per 7 km under RCP4.5, and −1 HDD per 5 km under RCP8.5.

On the other hand, Figure 4 shows that under RCP4.5, the projected increase in CDD remains relatively stable between the near future and the far future, over all of Europe, with an increase only evident over the Mediterranean area, and greater than 150 only over central Spain. Under the RCP8.5 the increase in CDD could be extreme over southern Europe, where CDD are projected to double in the far future compared with the recent past, or even climb by 300% or more in central and eastern Europe. Indeed, the current CDD values for southern Italy and Greece could become normal for central France and Hungary by the end of the 21st century. Moreover, during the last decades of the century, according to the projections of CDD, the use of cooling systems in mid-summer could be adopted in regions where it is currently unusual, such as southern Fenno-Scandinavia and the Baltic countries.

In summary, comparing projected CDD for the far future with that of the recent past, we can roughly approximate a north to south gradient, from the latitude of Oslo to that of Malta, of 1 CDD per 9 km under RCP4.5, and 1 CDD per 4 km under RCP8.5.

3.3. Trend analysis of HDD and CDD from 1981 to 2100

Figure 5 shows the average of the trend values for the period 1981–2100, resulting from the 11 EURO-CORDEX simulations for HDD and CDD, and under both scenarios (RCP4.5 and RCP8.5) analysed in this study. The linear trends are expressed, respectively, in HDD per year and CDD per year, and the values shown were computed as the ensemble mean of the trends of the individual simulations. If fewer than seven of the simulations project a significant trend (at the 95% confidence level) for specific grid points, the corresponding area is indicated with a grey background. This occurs only for areas where annual CDD values are very low or zero, such as Iceland, northern Scandinavia, Scotland, and the Alps.

The projected decrease of HDD for northern and eastern Europe is markedly larger under RCP8.5 than under RCP4.5. By the end of the 21st century, under RCP4.5

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a decrease of more than \(-10\) HDD per year is expected only in Scandinavia and Russia, whereas under RCP8.5 a decrease of more than \(-10\) HDD per year is expected almost everywhere in central, eastern, and northern Europe. It must be highlighted that the trends of HDD are found to be significant at the 95% confidence level (based on Student’s \(t\)-test) for every simulation and scenario, except for a few localized areas in Romania and Bulgaria and just two simulations.

The latitudinal gradient of the projected increase of CDD is evident. For both scenarios the positive trend increases southwards, with the Mediterranean region showing
the largest trends – up to about 4 CDD per year over southern Spain under RCP4.5, and up to about 6 CDD per year under RCP8.5. Under RCP4.5, less than seven simulations project a significant increase of CDD for the Alps, the Baltic countries, most of Ireland and Great Britain, Iceland, and Scandinavia, and less than three simulations project a significant increase for most of northern Europe. Under RCP8.5, such areas are limited to the Alps, northern Ireland, Scotland, Iceland, and northern Scandinavia. While Iceland and northern Scandinavia never show significant trends, due to extremely low annual CDD values, Figure 5 suggests that, under RCP8.5, regions with low or very low annual CDD – and therefore an almost negligible need for cooling buildings – are likely to become more scarce as the century passes, especially over central and eastern Europe, the Baltic countries and southern Scandinavia. Under both scenarios, southern, central, and eastern Europe are likely to experience a progressively higher energy demand to cool internal environments as the century passes. Taken together, the information from Figures 3–5 indicates that, under the more extreme RCP8.5, by the last decades of the 21st century, regions such as central France are likely to be characterized by annual CDD values as high as those for central Italy and Sardinia in the recent past.

Figure 6 shows the results of our analysis of uncertainty, computed as the relative standard error of the ensemble mean of the trend values shown in Figure 5. We first calculated the standard error of the single trend values (separately for CDD and HDD and for each scenario) for each of the 11 EURO-CORDEX simulations. We then averaged the 11 standard errors to obtain the ‘standard error of the ensemble mean’ of the trends. Finally, because the uncertainty related to absolute values follows the amplitude of the trend values, we divided the standard error of the ensemble mean by the ensemble mean. In Figure 6, the masked areas (present only for CDD) represent areas in which very low or zero annual CDD values lead to trends that are not statistically significant (at the 95% confidence level) for more than four simulations.

The relative standard error shown in Figure 6 is generally smaller under RCP8.5 than RCP4.5, and rarely exceeds 0.1 for both HDD and CDD. This is to be expected, because inter-model variability is smaller under the more extreme scenario, while under the moderate scenario, the agreement between simulations – especially in the central decades of the 21st century – is less clear. Under RCP4.5, the few regions with noticeable uncertainty include, for HDD, the most southern part of Spain and mountainous areas in Iceland, Norway, and central Europe, and for CDD, the Baltic countries and southern Fennoscandia. These patterns for CDD are expected for latitudes above 50°N, as they are characterized by low CDD values, and so relative standard errors tend to be larger. Mountain regions were also expected to show higher uncertainty than bordering areas, because of the complex topography, high inter-annual climate variability, and also because such areas are the least covered by the stations used to bias-adjust model outputs. The area with relatively large uncertainty around Sevilla, in Spain,
represents an exception, because the Mediterranean region is in general characterized by small uncertainty (excluding Cyprus). Southern Spain stands out as the region in Europe where differences between modelled and station-based degree-days are largest. Consequently, and particularly regarding HDD, the results for this region should be treated with caution.

3.4. Continental and regional HDD and CDD trends

The results presented previously relate to the scale of the grid cells (i.e. 0.11°). Here we discuss the regional patterns of the evolution of HDD and CDD throughout the 21st century. Figure 7 shows the scatterplots of the CDD and HDD trends during 1981–2100, for the eight macro-regions in Europe. In Figure 7, the left and right panels – representing RCP4.5 and RCP8.5, respectively – help to visualize the regions that are projected to show the largest increase (for HDD) and decrease (for CDD) in absolute values.

Despite its wide extent (roughly spanning latitudes from 43 to 72°N), European Russia shows a larger decrease in HDD than the converse increase in CDD. The same pattern is also projected for central Europe, eastern Europe, the islands of Great Britain and Ireland, and northern Europe (including Fenno-Scandinavia, Iceland, and the Baltic countries). Of these four regions, the last two show a very small increase (though not negligible under RCP8.5) in CDD. In contrast, parts of France (represented together with the Benelux countries), the Iberian Peninsula, and the Mediterranean region show a larger increase in CDD than the converse decrease in HDD, and so may be exposed to a potential increase in energy demand for cooling systems that will overweight the decrease in energy demand for heating systems.

Table 4 shows the ensemble mean trends for the eight macro-regions, and for Europe as a whole. As can be seen, the largest trends are observed for HDD over European Russia and northern Europe, and for CDD over the Iberian Peninsula and Mediterranean region. Looking at standard errors shown in Table 4 and reported below, we notice that for HDD the relative standard error is highest for European Russia and lowest for Great Britain and Ireland, whereas for CDD it is high over European Russia, but also over central and eastern Europe. For HDD, the ensemble mean trend for 1981–2100 for Europe as a whole is $-4.9 \pm 0.7$ HDD per year under RCP4.5, and $-8.4 \pm 0.7$ HDD per year under RCP8.5, with a standard error lower, in percentage, under RCP8.5. For CDD, the corresponding ensemble mean trend is lower, in absolute values (i.e. $0.8 \pm 0.2$ CDD per year under RCP4.5 and $2.0 \pm 0.2$ CDD per year under RCP8.5), with a relative standard error of about 25% under the moderate RCP4.5 scenario.

3.5. Population-weighted HDD, CDD, and EDD trends

Because of their theoretical background and definitions, trends in degree-day quantities are strongly influenced by temperature. However, energy demand depends also on many other factors. Empirical studies that correlate energy demand with HDD and CDD, usually find significant correlations with energy prices and income variables (Ruth and Lin, 2006; Isaac and Van Vuuren, 2009; Eskeeland Mideksa, 2010). Other factors include population...
Figure 7. Scatterplots of CDD versus HDD trends over 1981–2100 for eight macro-regions under RCP4.5 (left) and RCP8.5 (right). BRIT is for British Isles, SCAN for northern Europe (Fennoscandia plus Baltic Republics and Iceland), RUS for European Russia, FRA for France plus Benelux, CEN for central Europe, EAST for eastern Europe, IBER for Iberian Peninsula, and MED for Mediterranean region.

Table 4. Ensemble mean of the HDD and CDD trends over the period 1981–2100.

| Trend (1981–2100)     | rcp45       | rcp85       |
|-----------------------|-------------|-------------|
|                       | HDD/year    | CDD/year    | HDD/year    | CDD/year    |
| British Isles         | $-2.9 \pm 0.4$ | $0.1 \pm 0.0$ | $-5.2 \pm 0.4$ | $0.3 \pm 0.0$ |
| Northern Europe       | $-5.7 \pm 0.8$ | $0.1 \pm 0.0$ | $-9.4 \pm 0.7$ | $0.3 \pm 0.0$ |
| European Russia       | $-6.5 \pm 1.0$ | $0.6 \pm 0.1$ | $-10.9 \pm 1.3$ | $1.7 \pm 0.3$ |
| France + Benelux      | $-3.2 \pm 0.4$ | $0.8 \pm 0.1$ | $-6.0 \pm 0.4$ | $2.0 \pm 0.2$ |
| Central Europe        | $-3.9 \pm 0.6$ | $0.4 \pm 0.1$ | $-7.2 \pm 0.6$ | $1.1 \pm 0.1$ |
| Eastern Europe        | $-4.4 \pm 0.6$ | $0.7 \pm 0.2$ | $-7.9 \pm 0.7$ | $1.7 \pm 0.2$ |
| Iberian Peninsula     | $-2.5 \pm 0.3$ | $1.7 \pm 0.1$ | $-4.9 \pm 0.4$ | $4.1 \pm 0.2$ |
| Mediterranean region  | $-3.4 \pm 0.4$ | $1.9 \pm 0.2$ | $-6.1 \pm 0.3$ | $4.4 \pm 0.2$ |
| Europe                | $-4.9 \pm 0.7$ | $0.8 \pm 0.2$ | $-8.4 \pm 0.7$ | $2.0 \pm 0.2$ |

The ensemble mean of the trends is reported together with the standard error, computed as explained in the text in Section 2.3.

distribution and density (Taylor, 1981; Guttman, 1983; Shi et al., 2016), the type and insulation of buildings (Lorusso and Maraziti, 1998; Pérez-Lombard et al., 2008; Papakostas et al., 2010; Kurekci, 2016), and national laws on heating and cooling (Wang et al., 2010; Moustris et al., 2015). Some of these factors cannot be easily included in future projections. For example, it is next to impossible to predict how national laws may change in the next decades, while also considering that the energy market in Europe is becoming progressively more ‘green’ (Armaroli and Balzani, 2007; Buchan, 2010; Heide et al., 2010).

In order to account for possible increases or savings in energy demand over future decades, in this study we introduced the use of population weighting, as explained earlier in Section 2.3. Figure 8 shows the annual evolution of HDD and CDD during 1981–2100 under the two selected emission scenarios (RCP4.5 and RCP8.5). In Figure 8, the top panels show the HDD and CDD time series averaged over the entire EURO-CORDEX area, with no population weighting applied, the middle panels show the same quantities averaged over the area in which GEOSTAT 2011 population data are available, but without population weighting, while the bottom panels show the results for the GEOSTAT 2011 area with population weighting applied.

Overall, the evolution of the degree-day quantities with population weighting, for both scenarios, is very similar to that without population weighting, with small differences in the degree-day absolute values, as can be seen in the middle and bottom panels of Figure 8. HDD values are generally smaller with population weighting, due to the very cold and more sparsely inhabited regions of northern Europe having a lower trend than the European average. In contrast, the downsampling of these cold regions using population weighting is accompanied by a larger relative weighting for CDD values over hot regions in southern Europe, which are characterized by medium or high population density.

With or without population weighting, under both RCP4.5 and RCP8.5 the projections for HDD start diverging in the late 2030s, and those for CDD start diverging in the mid-2040s. According to both scenarios, the CDD trend shows a slight decrease in the last years of the 21st century.
century, whereas for HDD the decrease is continuous until the end of the century, but is projected to slow down after 2080 under RCP4.5. With or without population weighting, at the end of this century in Europe, the average annual HDD value will be approximately 25% smaller under RCP8.5 than that projected under RCP4.5. Conversely, at the end of the century the average annual CDD value is twice as large under RCP8.5 as under RCP4.5. Compared to the recent past (i.e. 1981–2010), the last decade of the 21st century is characterized by an average projected decrease in annual HDD of about 9% under RCP4.5, and 30% under RCP8.5, and a converse increase in annual CDD of about 45% under RCP4.5, and 170% under RCP8.5.

Similarly to Table 4, Table 5 shows the ensemble mean trends of HDD and CDD for the eight macro-regions, and for Europe as a whole, but this time accounting for population weighting, and over a slightly different region, because some areas are excluded as the corresponding population data are not available from the Eurostat data sets. It is noticeable that population weighting does not markedly change the trend values per year. This may imply that applying population weighting to projected climate data, without including population scenarios, might lead to incomplete results if one wants to estimate future energy savings.

Projections of population data are nowadays more frequently included in studies dealing with climate change impacts on degree-days and energy consumption (Shi et al., 2016). Consequently, we used population projections for the EU-28 countries, plus Iceland, Norway, and Switzerland, which are available from Eurostat at various levels of spatial aggregation (Eurostat, 2014). Data were selected at country level, for the years 2010, 2050, and 2080. We first obtained the annual HDD and CDD ensemble mean from the 11 EURO-CORDEX simulations for each grid point and for both scenarios. We then calculated, for each country, the corresponding population-weighted HDD and CDD values, by averaging the values from all grid points inside the country borders.
for the corresponding 10-year periods (2005–2015, 2045–2055, and 2075–2085). Finally, these values were summed to obtain energy degree-days (EDD) and were scaled (multiplied) by the corresponding population values for 2010, 2050, and 2080. Because multiplication of number of inhabitants and annual degree-days leads to a fictitious quantity that can be considered a simplified proxy for energy demand, we focus on the percentage difference per country between 2050 and 2010, and between 2080 and 2010.

Table 6 shows the percentage changes in EDD using population-projected data for 2010, 2050, and 2080, but also includes the corresponding changes using a constant population scenario, namely GEOSTAT 2011 population for 2010, 2050, and 2080. As anticipated earlier in Section 2, because the population projections from Eurostat databases do not include a measure of uncertainty of the data, the standard errors reported in Tables 5 and 6 have been calculated considering only the uncertainty introduced by the degree-day quantities. Because we used population projections at the country rather than sub-national level, and we did not couple population scenarios under different shared SSPs with climate scenarios, it must be emphasized that the results should be seen as a preliminary evaluation of expected energy demand due to a combination of climatological quantities (i.e. degree-days) and population.

Before discussing the EDD results, it should be pointed out that EDD are estimates of the physical energy demand for heating and cooling combined. However, cooling is generally more expensive than heating, and cooling devices have a lower energy efficiency than heating devices. Therefore, a given change in EDD should not be interpreted as a perfect equivalent change in energy costs or primary energy demand (Mima and Criqui, 2015). In Table 6 the names of countries with a projected population increase are highlighted in bold. For the other countries a population decrease is projected. If we use a constant population scenario (Table 6, left columns), almost all countries analysed are expected to see a decrease in combined energy demand for heating and cooling. This is due to the fact that HDD will progressively decrease during the 21st century under both RCP4.5 and RCP8.5, and this decrease will outweigh the projected increase of CDD under both scenarios and for all countries. The only exceptions are Cyprus and Portugal, and the latter only in the far future and under the more extreme RCP8.5.

When using population projections, the picture changes (Table 6, right columns). Despite the persisting warming trend, which will lead to lower HDD and higher CDD over Europe as a whole, for some countries the predicted population increase leads to an increase in energy demand, as reflected by higher EDD values in the near and far future compared with the present decade. These countries are located in northern Europe (Iceland, Norway, Sweden, and Denmark), the islands of Great Britain and Ireland, the Benelux countries, the Alpine region (Switzerland and Austria) and also southern Europe (Spain and Cyprus). Such an increase in energy demand for combined indoor heating and cooling is larger in percentage values for small countries that are expected to see a marked population increase, but is also greater than 10% for large but more sparsely populated countries such as Norway and Sweden. In contrast, large and densely populated countries such as Italy, Germany, and Poland are expected to see relevant energy savings due to the combined effects of population decrease and climate change.

4. Summary and conclusions

The central aim of this study was to investigate the likely evolution of HDD and CDD – which are frequently used to derive information on energy demand (De Rosa et al., 2014) – until the end of the 21st century over Europe. To this end, the annual trends of HDD and CDD from 1981 to 2100 were analysed, using the outputs (i.e. minimum and maximum temperature) of 11 bias-adjusted simulations from the EURO-CORDEX data set, for two emissions scenarios (RCP4.5 and RCP8.5). The results presented in this article demonstrate the marked differences, for both HDD and CDD, between the recent past (1981–2010), near future (2041–2070), and far future (2071–2100), as well as the linear trends of these indices from 1981 to 2100. Moreover, the importance of applying population weighting to degree-day estimates, and the use of population projections, are discussed with regard to projected...
Table 6. Changes of population-weighted EDD per country in near (2050, NF) and far future (2080, FF) versus recent past (2010) under RCP4.5 and RCP8.5, using constant population or changing population scenarios.

| Population | Climate scenario | Constant population (2011) | Changing population (2010, 2050, 2080) |
|------------|------------------|----------------------------|----------------------------------------|
|            | rcp45            | NF (%) FF (%)              | rcp85                                   |
| Country a  |                  |                            |                                        |
| Cyprus     | 2.1 ± 0.2        | 2.7 ± 0.3                  | 3.7 ± 0.2 10.0 ± 0.3                    |
| Greece     | −1.3 ± 0.1       | −3.8 ± 0.4                 | −1.6 ± 0.1 3.1 ± 0.2                    |
| Spain      | −1.7 ± 0.2       | −3.3 ± 0.3                 | −2.3 ± 0.2 5.8 ± 0.5                    |
| Italy      | −2.0 ± 0.2       | −6.1 ± 0.6                 | −3.9 ± 0.3 5.7 ± 0.4                    |
| Portugal   | −0.9 ± 0.1       | −3.0 ± 0.3                 | −0.7 ± 0.1 1.8 ± 0.2                    |
| Bulgaria   | −3.3 ± 0.4       | −7.1 ± 0.8                 | −4.4 ± 0.3 11.7 ± 0.9                   |
| France     | −5.9 ± 0.9       | −12.0 ± 1.8                | −8.8 ± 0.8 17.5 ± 1.5                   |
| Croatia    | −3.6 ± 0.5       | −9.0 ± 1.4                 | −6.0 ± 0.5 13.9 ± 1.1                   |
| Romania    | −3.9 ± 0.6       | −7.9 ± 1.3                 | −6.3 ± 0.5 14.7 ± 1.4                   |
| Slovenia   | −4.6 ± 0.7       | −10.4 ± 1.6                | −7.2 ± 0.6 17.4 ± 1.5                   |
| Hungary    | −3.8 ± 0.5       | −9.0 ± 1.2                 | −7.0 ± 0.7 16.2 ± 1.6                   |
| Switzerland| −5.2 ± 0.7       | −10.4 ± 1.5                | −7.8 ± 0.7 17.7 ± 1.7                   |
| Austria    | −5.0 ± 0.7       | −10.4 ± 1.5                | −8.0 ± 0.8 18.7 ± 1.8                   |
| Germany    | −6.0 ± 1.2       | −12.1 ± 2.4                | −8.3 ± 0.8 20.9 ± 2.1                   |
| Slovakia   | −4.6 ± 1.0       | −10.1 ± 2.1                | −7.7 ± 0.8 19.3 ± 1.9                   |
| Czech Republic | −5.4 ± 1.1   | −11.2 ± 2.2               | −7.5 ± 0.7 20.2 ± 2.2                   |
| Poland     | −5.9 ± 1.2       | −11.4 ± 2.0                | −8.0 ± 0.8 21.5 ± 2.1                   |
| Belgium    | −6.6 ± 1.3       | −12.6 ± 2.5                | −9.0 ± 0.9 21.0 ± 1.9                   |
| Luxembourg | −5.6 ± 1.1       | −11.5 ± 2.2                | −8.2 ± 0.8 18.4 ± 1.8                   |
| United Kingdom | −6.4 ± 0.7 | −11.8 ± 2.3             | −8.1 ± 0.6 20.9 ± 1.7                   |
| The Netherlands | −6.7 ± 1.3     | −12.0 ± 2.4           | −8.7 ± 0.9 21.1 ± 2.1                   |
| Ireland    | −6.7 ± 1.2       | −12.0 ± 2.3                | −8.7 ± 1.0 21.0 ± 1.9                   |
| Denmark    | −6.1 ± 1.5       | −11.6 ± 2.8                | −8.9 ± 0.9 22.4 ± 2.3                   |
| Lithuania  | −5.9 ± 1.3       | −10.7 ± 2.5                | −8.3 ± 1.2 21.5 ± 2.5                   |
| Sweden     | −6.1 ± 0.7       | −10.4 ± 1.2                | −9.0 ± 0.9 21.7 ± 2.2                   |
| Latvia     | −5.9 ± 1.5       | −10.5 ± 2.9                | −8.6 ± 1.0 21.6 ± 2.4                   |
| Estonia    | −5.9 ± 1.4       | −10.3 ± 2.7                | −9.1 ± 1.3 21.9 ± 2.4                   |
| Norway     | −5.8 ± 0.5       | −9.2 ± 1.0                 | −7.9 ± 0.6 19.4 ± 1.8                   |
| Finland    | −6.4 ± 0.7       | −10.3 ± 1.2                | −9.8 ± 1.0 22.3 ± 2.4                   |
| Iceland    | −4.8 ± 0.5       | −10.2 ± 1.3                | −7.1 ± 0.4 16.4 ± 0.8                   |

aCountries subject projected population increase are presented in bold. Reported uncertainties in EDD derive from uncertainties in degree-days only.

energy demands, as measured by HDD, CDD, and a third quantity, EDD, which is obtained as the sum of HDD and CDD. All of the results passed pre-validation tests, based on a comparison of the HDD and CDD climatologies for 1981–2010 derived from the EURO-CORDEX simulations, versus those previously obtained using an independent data set [described in Spinoni et al. (2015c)].

Our findings show a projected general decrease in HDD over Europe, which is more pronounced under RCP8.5 and in northeastern Europe, in particular over Scandinavia and Russia. Conversely, the projected marked increase in CDD in the Mediterranean region is in agreement with previous studies (Diffenbaugh et al., 2007), whereas it is not significant and also shows the largest uncertainty in northern Europe, and for some simulations in central Europe, under the moderate scenario (RCP4.5). Averaged over the entire European territory, the decreasing trends of HDD under RCP4.5 and RCP8.5 are likely to diverge approximately 6–10 years before the increasing trends of CDD do so. This suggests that climate change following the worst-case emission scenario (RCP8.5) is likely to cause earlier impacts on energy demand during winter, compared with the moderate scenario (RCP4.5). Moreover, although RCP4.5 is based on a progressive stabilization of GHG emissions after the middle of the 21st century (Thomson et al., 2011; IPCC, 2014b), the decrease of HDD and increase of CDD are only likely to stabilize in the last decade of the century. On the other hand, under RCP8.5, which assumes a continuous rise of GHG emissions (Riahi et al., 2011; IPCC, 2014b), the decrease of HDD and increase of CDD are likely to continue until the end of the century and beyond.

To account for the important impact of population density on energy demand and consumption, degree-day quantities are frequently adjusted by population weighting before reporting (Quayle and Diaz, 1980; Vaux et al., 2001; Zacharadas and Pashourtidou, 2007). Therefore, we computed population-weighted HDD, CDD, and EDD, at continental, macro-regional, and country scales, using the GESTAT 2011 high-resolution population data set (GESTAT, 2012). In absolute values, population weighting resulted in lower HDD and higher CDD values when averaged over all of Europe, mainly due to the low weights assigned to wide and more sparsely inhabited regions in northern Europe, which are characterized by large HDD and small CDD. However, the use of population weighting also resulted in very small differences in annual trends of

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HDD and CDD during 1981–2100, compared with the same trends without population weighting.

The use of a constant population scenario to estimate future energy demand for cooling and heating buildings, might be a limiting factor, especially in a rapidly changing world in which population is generally projected to increase, at a rate which depends on the shared SSP considered (Samir and Lutz, 2014; Jones and O’Neill, 2016). Population scenarios for Europe generally follow global patterns (De Beer and van Wissen, 2013), but some regions in Europe are expected to see a population decrease (Rees et al., 2012), in particular in southern and eastern Europe (European Commission, 2015). Using country-level population projections for 2050 and 2080, provided by EUROSTAT (Eurostat, 2014), we analysed the combined evolution of population and EDD, and compared the results with those based on a constant population scenario.

The analysis has been performed for 30 countries (i.e. EU-28 plus Iceland, Norway, and Switzerland, but excluding Malta). Using a constant population scenario, only Cyprus is expected to see a continuous increase in EDD under both climate scenarios (RCP4.5 and RCP8.5). All other countries are expected to see a decrease in EDD, due to a progressive decrease in HDD which will outweigh the converse increase in CDD. Consequently, if population remains constant, the projected climate warming will cause EDD generally to decrease over Europe, and so one possible benefit linked to future warming might be a net energy saving, as the 21st century progresses. However, the situation is different if population projections are used. In particular we found that a population increase causes EDD to increase under both climate scenarios (RCP4.5 and RCP 8.5). Such an increase can be expected especially for northern Europe, the Benelux countries, the islands of Great Britain and Ireland, the Alpine region, Spain, and Cyprus, potentially causing an increase in energy demand despite the projected warming.

The use of population projections must therefore be further explored. The present study prepares the ground for a more refined analysis, in which we plan to include an ensemble of multi-model population projections – together with the corresponding uncertainties – based on various socio-economic scenarios. Furthermore, we plan to move from country level to smaller administrative units such as the EU’s NUTS3 statistical regions (http://ec.europa.eu/eurostat/web/population-demography-migration-projections/ population-data). As a further possible improvement, we plan to extend the analysis performed for HDD and CDD to two other temperature-based indicators analysed in the earlier study by Spionini et al. (2015c), namely GDD (McMaster and Wilhelm, 1997) and the Winkler index (Winkler et al., 1974).

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