Degree-Days and Agro-meteorological Indices in CMIP5 RCP8.5 Future Climate—Results for Central and Southeast Europe

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Abstract The present paper is continuation of our recent study and analyzes the potential changes of residential heating and cooling degree-days as well as three stakeholder-relevant indices of agro-meteorological change (growing season length, sum of the active and sum of the effective temperatures) for Central and Southeast Europe over near past (1975–2004), near (2021–2050) and far (2070–2099) future periods. All indicators were calculated from the output data of our simulations with the regional climate model RegCM driven by the ERA-Interim reanalysis for the near past and by the global circulation model HadGEM2-ES under RCP8.5 CMIP5 radiative forcing scenario for the future periods. The validation of the model-based indices against their counterparts, computed from the observational dataset E-OBS, shows that the model reproduces their spatial variability and magnitude generally well. A linear bias correction of the considered indices is also demonstrated. Consistent with the general trend of the mean and extreme temperatures over the region, the study reveals a decrease of the heating degree days and considerable increase of the cooling degree days and the agro-meteorological indices practically over the whole domain in the future. The detected changes are fairly not symmetrical - the relative increase of the cooling degree days is significantly bigger than the decrease of the heating degree-days.

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1 Introduction

Nowadays there is a strong degree of agreement that the climate change is the defining challenge of our time. It will exert influence on the ecosystems, on all sectors of the international economy, and on the human health and quality of life [25, 26, 39]. The global warming tendencies and the linked regional climatic changes over Central and Southeast (CSE) Europe have been widely studied in the last decades based on in situ measurements [1, 2, 16], assimilated surface observations [4, 12, 36], reanalysis [6] global models [5, 38] and regional climate models [9, 29, 34]. Most of these studies are focused on the second half of the twentieth and the first decade of the twenty-first century, clearly evidencing that, similarly to the global and continental trends, the regional climate got warmer during the period. There is also an overall consensus that the projected changes in the mean and extreme (i.e. minimum and maximum) temperatures stand out in the region indicating a considerable intensification of heat stress in the future [10, 11, 35, 39].

Beside the mentioned effects, the ongoing and projected future climate changes have direct and indirect impact on managed systems like heating, ventilating and air-conditioning industry [3, 28, 41] as well as the agriculture [23, 24, 30]. Space heating and cooling is responsible for a large fraction of European energy use [17]. Agriculture is probably the sector most dependent on climate. Agricultural production is highly dependent on weather conditions and extreme weather events can have a dramatic impact on the crop yield [23, 24, 37]. The increase of temperature in the region, together with more frequent severe winters and summer heat waves may lead to a change in energy consumption and agricultural production [28, 41]. The linkage of the ambient daily mean (*tg*), minimum (*tn*) and maximum (*tx*) temperatures and the energy needs for air-conditioning or heating buildings as well as the crop productivity can be quantified by means of numerical indicators, calculated from these input parameters. They are rough surrogates for how climate change is likely to affect both sectors [22, 41].

The present study analyses the potential changes of residential heating and cooling degree-days (HDD and CDD) as well as three stakeholder-relevant indices of agro-meteorological (AM) change (growing season length, sum of the active and sum of the effective temperatures) for CSE Europe over near past (1975–2004), near (2021–2050) and far (2070–2099) future periods. All indicators were calculated from the output data of our simulations in 20 km grid spacing with the regional climate model (RCM) RegCM driven by the global circulation Model (GCM) HadGM under the CMIP5 radiative forcing scenario RCP8.5. The present paper is natural continuation of our recent work, documented in [27] and fits in the same conceptual framework.

The RCP8.5, being the scenario with the strongest radiative forcing among all others, deserves special attention due to the most expressive manifestation of the projected climate changes [39, 42].

The paper is structured as follows: Concise description of the RCP8.5 scenario and the used model set-up is in Sect. 2. The theoretical background of the applied indicators is described in Sect. 3. The core of the article is Sect. 4, titled 'Calculations and Results'. The concise conclusion remarks are in Sect. 5.

2 RCP8.5 Scenario and Model Set-Up

In climate change research, scenarios describe plausible trajectories of climate conditions and other aspects of the future [42, 43]. Along with information on other related conditions such as land use and land cover, emissions scenarios provide inputs to climate models. The Coupled Model Intercomparison Project (CMIP) is a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models (CAOGCMs) which provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access [42]. The fifth phase of CMIP, CMIP5 experiment uses new emission scenarios called representative concentration pathways (RCP) [33, 43] to assess the interactions between the human activities on the one hand and the environment on the other hand, and their evolution. They are named according to the radiative forcing level at 2100 [33], with the numbers representing the 2100 radiative forcing increase relative to pre-industrial levels in $W\,m^{-2}$. Among other RCPs, the RCP8.5 is the scenario with the highest concentration of greenhouse gases (GHG): it 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. Note that RCP8.5 assumes radiative forcing levels continue rising after the end of the twenty-first century.

As in [27], the simulation of the future climate was carried out using RegCM4.4, a limited-area, hydrostatic, compressible, sigma-p vertical coordinate model maintained at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy [21]. The model is flexible, portable and easy to use, combining efficiency and high performance skill. It can be applied to any region of the world, with grid spacing of down to about 10 km (hydrostatic limit), for a wide range of studies. Subsequently, it is widely exploited and there are a number of previous studies that evaluated the model performance around the world (see [19, 21, 34] and references therein). The entire experiment covered the near past (1975–2004), near (2021–2050) and far (2070–2099) future periods, with initial and boundary conditions taken from the Hadley Centre Global Environment Model version 2, Earth-System configuration (HadGEM2-ES) [14] CAOGCM. In the comprehensive study [35], which uses also HadGEM2-ES as driving model, is stated that this CAOGCM is characterized by a relatively good level of performance among CMIP5 models for most regions (including the Mediterranean region).

Our modelling group has a previous, partially project-driven, experience in the exploration of the model RegCM for simulation of the near past, present and projected future climate [18, 20] as well as in assessments, based on RegCM-derived indices [26].

3 Heating, Cooling Degree-Days and AM Indices

The HDD and CDD are, similarly to the climate indices [1, 44], an attempt to objectively extract information from daily weather data (observations or model output as in case) that answers questions concerning energy demand and/or consumption in the business and residential heating and cooling sector [40]. Thus, they are likely to display the same types of variability as the temperature data on which they are based which makes them a common climatological indicators. The units of measurement of the HDD and CDD are degree-days which, according the proper proposal in [28], will be noted henceforth as °D. The heating and cooling requirements for a given structure at a specific location are considered, in some degree and beside the influence of the other factors, proportional to the number of HDDs and CDDs at that location. The method assumes that the energy needs for a building are proportional to the difference between the daily mean and extreme temperatures and a base temperature (*tb*). The base temperature is the outdoor temperature below or above which heating or cooling is needed. In terms of degree-days, the annual energy consumption, Q_{year} (W day), can be calculated according [3] as:

$$Q_{year} = \frac{K_{tot}}{\eta} DD, \tag{1}$$

where K_{tot} is the total heat-transfer coefficient of the building in W °C^{-1}, η is the dimensionless efficiency of the heating or cooling system and DD is the value of degree-days for heating or cooling. In contrast of some collections of climate indices [44], the theoretical formulation of the CDD and HDD is not standardized; their computation can be performed in different ways, depending on the nature and scope of the study as well as availability of input data. Computation methods range from simple approaches, based on monthly or annual temperature, to more sophisticated models [40, 41]. As in [27], in the present study we use the developed in the United Kingdom Meteorological Office (UKMO) [13] and successfully applied in [40, 41] method. According it, daily HDD and CDD are calculated based on a comparison of *tn*, *tg* and *tx* with the selected in advance *tb*, taking account of fluctuations of daily air temperature around the base temperature, as well as the asymmetry between daily mean temperature and diurnal temperature variations, as shown on Table 1.

Hence the study is on annual basis, we summed the daily values. As in the original proposal [13], *tb* is set on 15.5 °C for the HDD- and on 22.0 °C for the CDD-computation. Other definitions of these indicators, based solely on *tg*, have a jump

Table 1 UKMO methodology for computing daily HDD and CDD

Condition	HDD =	CDD =
$tx \leq tb$ (uniformly cold day)	$tb - tg$	0 (no cooling is required)
$tg \leq tb < tx$ (mostly cold day)	$(tb - tn)/2 - (tx - tb)/4$	$(tx - tb)/4$
$tn < tb < tg$ (mostly warm day)	$(tb - tn)/4$	$(tx - tb)/2 - (tb - tn)/4$
$tn \geq tb$ (uniformly warm day)	0 (no heating is required)	$tg - tb$

discontinuity when daily mean temperature falls below the base temperature. The methodology of UKMO does not exhibit such a discontinuity [17].

It is worth to emphasize also, that in present work the daily mean temperature is independent input parameter, rather than estimated as arithmetic average between *tn* and *tx* as in [40, 41].

In the last decades has been done significant research in many countries on temperatures critical to plants, and this, along with the aggregate evaluation of thermal resources, has made possible a substantially more accurate determination of climatic heat provision to crops [31]. The effects of climate change clearly appear in agriculture and forestry in the considered region. Production of these sectors is strongly influenced by the climate-related measures as the growing season length (GSL), accumulated active and effective temperatures (AAT and AET). These quantities are valuable AM indicators relevant for cultivated plants phenology and active growth of crops [4, 24, 30, 37].

According the common definition of the European Climate Assessment & Dataset (ECA&D) project [15] and the Expert Team on Climate Change Detection and Indices (ETCCDI, [44]), the GSL is the annual count of days between first span of at least 6 days with $tg > tb$ and first span after July 1 (in Northern Hemisphere) of at least 6 days with $tg < tb$. In this definition $tb = 5$ °C which is threshold temperature for the cold-tolerant species. The threshold temperature for the thermophile species is 10 °C and in the present study, due to the geographical location of the region, we apply this value. The units of measurement of the GSL are, obviously, days.

As the GSL, the AAT and AET are calculated also on annual basis and are defined as:

$$AAT = \sum_{i=iu}^{i=io} tg(i), \quad AET = \sum_{i=iu}^{i=io} \max\left(tg(i) - tb, 0\right), \qquad (2)$$

where $tg(i)$ is the mean daily temperature in the day of year (DOY) i, iu is the DOY of the start, and io the DOY of the end (cessation) of the GSL. The units of measurement of the AAT are degree-days, noted as the units of the HDD and CDD °D.

The degree day method, which expresses numerically the relationship of plant development and growth to atmospheric temperature, was developed in the United States in the first half of the twentieth century. Total active and effective temperatures, subsequently the values of AAT and AET as well as ranges for GSL, have been established for many crops. These methods of expressing crop heat requirements are widely used for agricultural climate evaluation in the former Soviet Union, Bulgaria, Poland, Romania, and a number of other countries [37] which motivates their selection in the present study.

4 Calculations and Results

First, the RegCM-output parameters *tn*, *tg* and *tx* are mapped onto regular $0.25° \times 0.25°$ lat–lon grid. The considered indices are computed according the definitions in Sect. 3, by purposely-build by the authors procedures. The analysis in the present study is focused on the multiyear (i.e. over the whole 30-year long periods) means (MM).

The credibility of the model set-up to reproduce the considered indices should be examined. The validation of the results is performed in the traditional way, comparing of the model-based indices against their counterparts, computed from the observational dataset E-OBS v19.0 [15], accepted as reference. The relative bias (RB), i.e. the metrics

$$RB = (I_M - I_R)/I_R, \tag{3}$$

where I_M and I_R are the model and reference values of any of the considered indices respectively, is presented on Fig. 1.

Similarly to some ETCCDI-indices, for example, the 'tropical nights', the CDD is practically meaningful only in low elevation areas (i.e. below 1000 m) which are particularly exposed to persistent and intense warm spells in summer [4, 12, 38].

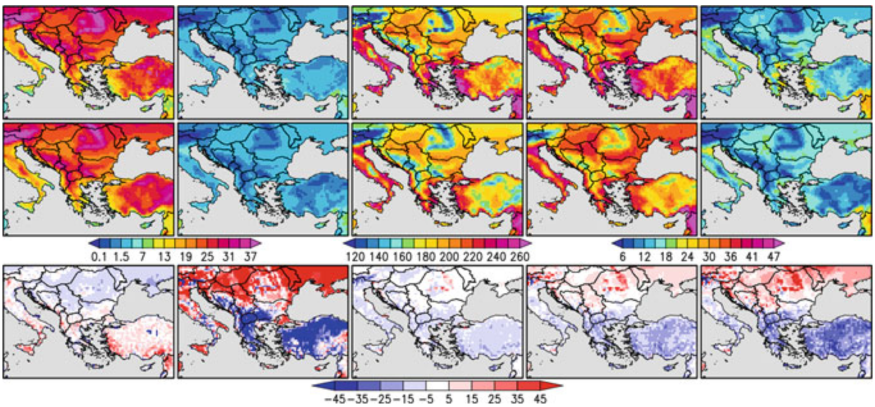

Fig. 1 From left to right: MM for the 1975–2004 of HDD, CDD, GSL, AAT, AET from E-OBS (first row) and RegCM-output (second row). The units of HDD, CDD, AAT and AET are 100 °D and of GSL—days. The RB (in %) is shown on the third row

Figure 1 shows that the model reproduces the spatial variability and magnitude of the all indices, except CDD, relatively well—the spatially prevailing RB is in the range -15 to 15%.

The RegCM simulations, as these from any other regional climate model, often show some, in certain cases considerable, deviations from observations [9, 21, 34]. This common methodological problem is partly inherited from the driving global model and has led to the development of a number of correction approaches, known with the common name bias correction (BC). BC first of all aims to adjust selected statistics of a climate model simulation to better match observed statistics over the present-day reference period. The basic assumption is that bias changes are negligible compared to climate change or, equivalently, that the bias itself is time-invariant [32]. The general view in the expert community is that the bias-corrected climate change signal is more reliable compared with the uncorrected one. Subsequently, BC model output is more suitable for impact assessments and thus we will apply it on the considered indices.

Following the proposed in [32] and adopted in [7, 8] notation, the simulated present-day model time series of length N of chosen variable will be denoted as x_i^p, the corresponding reference time series as y_i^p. The mean of the uncorrected model over the considered near past period (i.e. 1975–2004) μ_{raw}^p can be estimated as $\hat{\mu}_{raw}^p = \overline{x_i^p}$ (the hat denotes traditionally the estimator and the bar—averaging in time), the corresponding real mean μ_{real}^p as $\hat{\mu}_{real}^p = \overline{y_i^p}$.

The most simple approach used for BC is the so-called delta change approach. It is widely used in climate impact research [32]. In its most basic application, performed in the present work also, a time series of future climate is generated as:

$$x_{i,corr}^f = y_i^p + (\overline{x_i^f} - \overline{x_i^p}). \tag{4}$$

The quantity $\overline{x_i^f} - \overline{x_i^p}$ is actually the model derived climate change signal. Thus, Eq. 4 could be treated as observed time series corrected with the simulated climate change. The method based on Eq. 4 is called correspondingly additive delta change method. The delta change approach and its modifications are investigated in [7, 8] considering ETCCDI climate indices. One of the newly proposed idea was to apply Eq. 4 directly on the indices, rather on the parameters (i.e. *tn*, *tg*, *tx* and the daily precipitation sum), used for their calculation. One of the basic findings in [7, 8] is that this approach is reasonable in the case of the thermal indices and thus we will implement it here, as shown on Figs. 2 and 3. The relative climate changes (RCC), which is defined similarly to the RB in Eq. 3:

$$RCC = (I_F - I_P)/I_P, \tag{5}$$

where I_F and I_P are the model simulation output for the future (near or far) and the near past of the considered indices respectively, are also presented on these figures.

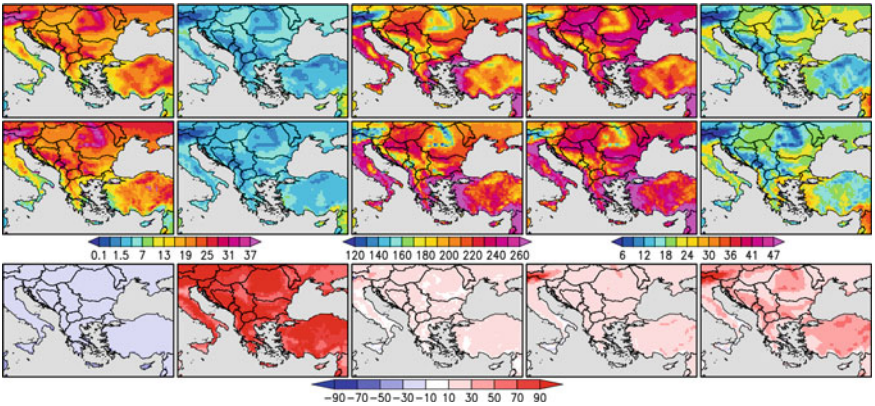

Fig. 2 From left to right: MM for the NF of HDD, CDD, GSL, AAT and AET from the raw RegCM output (first row) and after the BC (second row). The units are as on Fig. 1. The RCC (in %) are shown on the third row

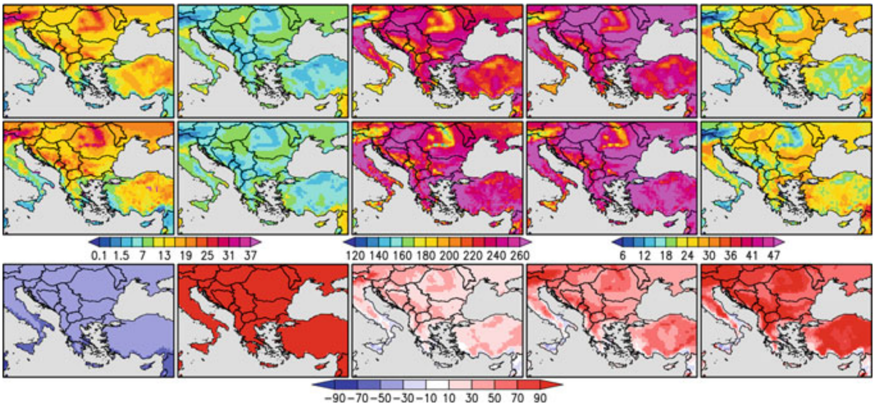

Fig. 3 Same as Fig. 2 but for the FF

Most apparently, the spatial patterns of the uncorrected and corrected versions of all indices, shown on Figs. 2 and 3 are practically identical. This result is direct consequence of the generally good agreement between the reference and the model output for the near past, shown on Fig. 1 and commented above. The RCC demonstrates the definite evolution of the considered indicators—distinct and spatially dominating increase of the 'warm' indicators (CDD, GSL, AAT and AET) and decrease of the 'cold' one (i.e. the HDD). It is worth emphasizing, that for the both future periods the relative increase of the CDD is significantly bigger than the relative decrease of the HDD—the decrease of the HDD in the FF, which is almost homogeneous distributed, is −50 to −30% and increase of the CDD is practically everywhere above 90%.

The pan-European and comprehensive study [41] reveals similar tendencies. Comparing the differences in degree-days between the periods 2041–2070 and 1981–

2010, the authors discover overall increase of the CDD in the projected future climate which peaks over the Mediterranean region and the Balkans. Conversely, the HDD is expected to fall: the decrease in HDD over the same region is (on average) about −200 °D under RCP4.5. However, in relative terms, the decrease in HDD is largest in Southern Europe, where values are projected to be reduced (on average) by 30% under RCP4.5. The local study [28], outlines coherent outcomes despite the different modelling and scenario set-up. Although not directly comparable, our results are in principal agreement with the outcomes of these and some older studies.

5 Conclusion

It should be noticed that this research, which is the continuation of our previous [27], does not quantify future changes in heating or cooling residential energy demand and the general agro-meteorological conditions, but gives an overview of projected changes in the considered indicators which point to the sign and trend of changes in these sectors.

RegCM has proven to reproduce the magnitude and spatial variability of HDD, as well as GSL, AAT and AET very well and thus the applied bias correction do not alter significantly the result.

Our main findings show unambiguously a projected general decrease in HDD and all AM indicators over CSE Europe, which quantitatively is stronger expressed as in the scenarios with weaker radiative forcing (i.e. RCP2.6 and RCP4.5) in the far future. Conversely, the CDD is expected to increase. The detected changes, which agrees with most recent studies [28, 41], are direct consequence of the expected general temperature tendencies in the region and are natural continuation of the tendencies revealed from the analysis of historical records of the near past [2, 5, 12, 16, 36, 38].

As emphasized in [17], a decrease in the demand for space heating can significantly decrease overall energy use in Europe, but this gain can be offset in part or completely by an increase in cooling demand. Furthermore, heating is delivered to end users in different ways (individual boilers powered by oil, gas and coal, and electricity and district heating), whereas cooling is supplied currently almost exclusively through electricity. As a result, a given change in cooling demand is generally associated with larger costs, a larger change in primary energy needs and larger impacts on the peak capacity of supply networks than the same change in heating demand.

The estimated changes of the AM indices in projected future climate could be also prerequisite for deep ecological and economical consequences. Longer growing seasons, as well as bigger AAT and AET, may allow for a greater diversity of crops (including those with long maturation periods), and the potential for multiple harvests on the same land. Conversely, both irrigation needs and the risk from invasive species, pests and pathogens may increase [22].

The results of the present study could be useful as scientific basis for the long-range policy of energy management and of the agricultural sector within CSE Europe.

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