



Modelling climate analogue regions for a central European city

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Abstract

In this study, we describe a methodology to derive climate analogue cities for spatially highly resolved future climate scenarios. For the computation, a reduced and in hindsight bias-adjusted EURO-CORDEX EUR-11 dataset is used based on two climate scenarios (RCP4.5 and RCP8.5). A total of 389 European cities are processed by the algorithm, which uses five statistical climate variables (2-m air temperature average and amplitude, precipitation sum and amplitude, correlation between 2-m air temperature average and precipitation sum). Additionally, extreme weather events (hot days, summer days, tropical nights, extreme precipitation events) are calculated for further comparison and validation. Finding an appropriate analogue permits a more accurate derivation and depiction of necessary climate adaptation efforts and therefore assist decision-making in city planning. As an example of our method, we searched for plausible climate twins for the mid-sized city of Aachen (Germany) at the end of the twenty-first century. Our results show that the French city of Dijon is highly likely to become Aachen's climate twin by the end of the century for RCP4.5. As for the scenario RCP8.5, no clear European analogue city could be determined, indicating that the city might enter a novel climate. The nearest match suggests the cities of Florence and Prato in Tuscany. However, considering climate indices, the encompassing region of the French–Spanish city triangle Bordeaux–Toulouse–Bilbao is a better fit. The developed algorithm can be applied to any of the cities included in the dataset.

Keywords Climate analogue cities · Climate twins · Climate change · Regional climate models · EURO-CORDEX

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1 Introduction

Urban spaces account for 3% of the global terrestrial surface, yet they cause 78% of energy-related carbon emissions that contribute to global climate change (Grimm et al. 2008). Urban areas are acknowledged to be important ‘first responders’ in climate change adaptation and mitigation because they are wealthy and innovative centres that possess the tools and resources to tackle these environmental and ecological challenges (Rohat et al. 2017; Rosenzweig et al. 2010).

However, the complexity of climate governance is often underestimated, not only within the research community but also in society as those strategies have to be implemented on multiple levels, across a variety of sectors, alongside a multitude of actors (Grafakos et al. 2018). In addition to this, a knowledge gap, also referred to as a ‘consensus gap’, that exists between the scientific and the public community might decelerate or even completely hinder the implementation of climate policies. To appropriately communicate the urgency of climate change and to overcome the barriers of public recognition of its linked risks, visualisation is a commonly used awareness-raising tool (Bastin et al. 2019; Fitzpatrick and Dunn 2019; Rohat et al. 2017). Thereof emerged a new geographical approach which is currently experiencing a revival in climate research: the scientific concept of climate analogue regions or ‘climate twins’ (Kopf et al. 2008; Ungar et al. 2011). Hallegatte et al. (2007), who took on a pioneering role in climate analogue research by focusing on urban areas, defined a climate analogue region as a region that is currently subject to climatic conditions which are similar to future, projected climatic conditions in the study area. If no adequate climate analogue region is to be found, Williams and Jackson (2007) qualify the climatic conditions as ‘novel’.

Building on these definitions, Kalkstein et al. (2008) used the theoretical concept to investigate urban health policies and potential mortality rates by applying European extreme weather events on U.S. American cities. Beniston (2014) computed the velocity of longitudinal and latitudinal shifts, enabling the capture of the geographical change of isotherms throughout the use of cities. The following large-scale investigations of Rohat et al. (2017; 2018), Fitzpatrick and Dunn (2019) and Bastin et al. (2019) finally put climate analogue cities on the map.

Climate change will have an impact on the frequency and intensity of extreme weather events and will exert significant pressure upon the urban environment. However, what must not be forgotten is that cities can partially be held responsible for their own climate. City size and topography, building density, materials and height, artificial heat sources, green as well as water spaces all impact the local climate (Kuttler 2011; Oke et al. 2017). Therefore, results on climate analogue regions should not be taken as a forecast but rather as an illustration.

The goal of this research is to derive climate analogue cities for spatially highly resolved future climate scenarios (0.11°, 12.5 km) that can be flexibly applied to any single study area. We want to expand the focus of climate analogue research to medium-sized cities, as the major part of urban population lives in cities with fewer than 300,000 inhabitants (UN 2019). Most previous studies, especially for Europe, were mainly interested in major urban areas. For this reason, we use an unusually large dataset of possible analogues, consisting of 389 European cities. We exemplarily chose the German city of Aachen as a case study area as it is highly comparable to other mid-sized urban areas on the continent. The method, however, can be applied to any other city of interest and might be of interest for the application in planning departments of individual communities. So far, a few German

cities have been involved in European studies such as Hallegatte et al. (2007) or Beniston (2014), but no German city has been the centre of a climate analogue study, yet.

Additionally, we combine several important aspects of previous approaches to find climate analogue cities. We use two representative concentration pathway (RCP) scenarios and a large regional climate model (RCM) ensemble with 15 projections for RCP4.5 and 27 for RCP8.5 and take into account both climate variables and indices. Up to this point, studies using more than one RCM usually calculated a multi-model mean or used additional RCMs only for verification of results conducted with a single RCM. Here, we suggest a novel strategy of determining the most likely climate analogue with multiple RCMs. Because we focus on a single city of interest, we are able to show the determination process in more detail. We calculate one analogue city per ensemble member and analyse how many times a possible analogue city is picked. This highlights the full range of possible climate analogues and makes the selection process more transparent compared to methods where only a single analogue city is presented. The second part of this paper focuses on the study area and the assembly process of the dataset regarding data sources, variables, scenarios, time spans and bias adjustment. The third part deals with results and their interpretation. Subsequently, all findings are concluded and an outlook is provided.

2 Data and methods

2.1 Exemplary study area

Aachen (50.77° N, 6.07° E) is a mid-sized German city with an urbanised area of approximately 160 km² and 250,000 inhabitants, situated at the border triangle with Belgium and the Netherlands. The city is part of the Eifel landscape in the federal state of North Rhine-Westphalia (NRW) (Buttstädt and Schneider 2014; LANUV 2019). The city lies in a river basin with a diameter of 5–8 km. The city centre is located at an altitude of approximately 158 m above sea level, whereas the highest points can be found at the southeast city border at almost 360 m. Due to this altitudinal range and the proximity to the rural, hilly landscapes and plateaus in the south, Aachen's climate is particularly influenced by topography (Stadt Aachen 2014). With its mid-latitude Western European location, Aachen is climatologically influenced by the Azores High and the Icelandic Low and prevailing westerlies. According to the Köppen–Geiger climate classification system, Aachen has an oceanic Cfb climate with mild winters and warm summers (Kottek et al. 2006). We chose Aachen because it is a typical mid-sized, mid-European city, which makes it a good candidate for a case study. A method which works here, probably works for a lot of other urban areas. Cities of that size are not likely to produce an urban effect in the RCMs. Therefore, a method that is universally valid should analyse the regional climate in which a city of interest and its possible analogue cities find themselves, rather than the actual urban climate of the cities.

2.2 Climate analogue cities samples

The selection process to identify potential climate twins for the city of Aachen used as a criteria population census data. The data were obtained from the Urban Audit 2020 and European Spatial Planning Observation Network (ESPON) database that includes 358 cities across 30 European countries (Reckien et al. 2014). Geodata of Polish cities had to be

added manually since they were left out in the Urban Audit. Also, Greek cities were not included because no census data were found in the ESPON database. Setting the threshold at 150,000 urban inhabitants and including capital cities, a total of 392 European cities were identified and make up the climate analogue city sample.

2.3 Climate data

Regional climate change projections of the ‘COordinated Regional Climate Downscaling EXperiment’ (CORDEX) project constitute a state-of-the-art and widely used dataset to assess regional climate change, improve process understanding, and drive impact models (Boé et al. 2020; Fernández et al. 2019; Giorgi et al. 2009; Giorgi and Gutowski 2016; Jacob et al. 2014; Jacob et al. 2020; Junk et al. 2019; Kotlarski et al. 2014; Kotlarski et al. 2017; Vautard et al. 2021). CORDEX is part of the World Climate Research Program (WCRP). Data are available as open-access research data through the Climate Data Store (CDS) as part of the Copernicus Climate Change Service (C3S) and the Earth System Grid Federation (ESGF) data nodes.

RCM data of EURO-CORDEX, the European initiative of CORDEX, are provided on a EUR-44 (0.44°, about 48 km) and EUR-11 (0.11°, 12.5 km) resolution grid (Gutowski et al. 2016). The EUR-11 model domain extends over Europe from 27° N to 72° N and from 22° W to 45° E. Due to these spatial limitations, the total number of potential analogue cities was reduced to 389 given that three cities of the Canary Islands were excluded from the grid (Rennie et al. 2021).

A methodology as described in Rennie et al. (2021) was used to extract daily time series for the 389 positions of the analogue city sample. The extraction uses a bilinear resampling algorithm, calculating the spatial mean of the four nearest RCM grid points, weighted by their distance from the city points. No height correction implementation and a time series merger was used to obtain time series covering 1950 to 2100 at a daily, monthly and yearly temporal resolution. Kreienkamp et al. (2012) underline that a better representation is given by consideration of multiple grid points instead of single coordinates. By applying the stated methodology, these requirements are met.

The EURO-CORDEX model ensemble in the CDS, currently consists of 9 global climate models (GCMs) and 14 RCMs with various GCM-RCM combinations. RCMs are transient, driven by GCM control and scenario simulations in a one-way single-nest model setup. This study uses a multi-model-ensemble approach to describe possible uncertainties and to cover ‘the range of climate changes that can be expected’ (Kreienkamp et al. 2012). However, not every model ensemble qualified for our analysis due to heterogeneity based on scenarios, variables and time spans (see Table 2 and ‘Section 2.3.3’).

2.3.1 Scenarios

Climate projections based on the RCP scenarios (RCP4.5 and RCP8.5) were used in this study (van Vuuren et al. 2011). Projections using RCP6.0 were not available for all necessary time series and variables. Data for RCP2.6 were available but were not taken into account as—for the present day—given that this scenario relies on fast responses in climate adaptation and mitigation technologies, RCP4.5 and RCP8.5 are considered to more accurately display mid- and end-century greenhouse gas emission levels (Schwalm et al. 2020). Kreienkamp et al. (2012) support this method of using a scenario with a higher and one with a lower radiative forcing.

2.3.2 Climate variables

In accordance with the IPCC (2014), essential climate variables as introduced by the Global Climate Observing System (GCOS 2003) include temperature and precipitation. Although other important variables such as wind or humidity play a vital role depending on the research objective, this study only focused on the former predictors as the process of finding a city analogue becomes more complex with each variable. Like Rohat et al. (2017) described, finding an analogue for every variable would be highly improbable due to the uniqueness of each climate. Additionally, many studies that focused on climate analogues only relied on temperature and precipitation (Beniston 2014; Hallegatte et al. 2007; Kopf et al. 2008; Ungar et al. 2011). To ensure the precision and relevance of our calculations, three climate indices that impact human health and allow assumptions about future heat stress as well as one index that can have considerable implications on urban society were added. Table 1 lists the extracted climate variables, the derived climate statistics as well as the stated climate indices. The names of the climate statistics are derived from the CORDEX nomenclature (ECMWF 2022). *Tasmax_hot*, *tasmax_summer*, *tasmin* and *pr_20* as defined in Table 1 are based on definitions by the Deutscher Wetterdienst (2021a) and are part of the core indices for detecting changes in climate extremes agreed upon by the Expert Team on Sector-specific Climate Indices (ET-SCI) on behalf of the world Meteorological Organization (WMO) (Alexander and Herold 2016). They are widely used in recent studies and therefore have a high degree of comparability (Chapagain et al. 2021; Herold et al. 2018; Nakaegawa and Murazaki 2022; Yosef et al. 2019). Note that *pr_35* (annual sum of days with ≥ 35 l/m² precipitation in 6 h) and *pr_60* (annual sum of days with ≥ 60 l/m² precipitation in 6 h) are not considered as, amongst others, Jacob et al. (2014) state that high precipitation intensities ‘above 30 mm per day hardly occur in GCM simulations’. We use threshold indices rather than indices defined by percentiles, because we want to find similar climates rather than comparing the effects of climate change in different regions of the world. The thresholds define the acceptable tolerance, in which a variable of a possible climate analogue city can lie to be seen as similar. These thresholds were used to standardise the variables with weighting factors (‘Section 2.5’).

2.3.3 GCM-RCM ensemble members

Due to the lack of temporal homogeneity throughout the datasets, further capacity and organisational constraints were defined (Table 2). The British GCM (MOHC-HadGEM2-ES) has a 360-day calendar; thus, it was excluded from calculations. The Swedish RCM (SMHI-RCA4) and the Italian RCM (ICTP-RegCM4-6) only cover the time period up to the year 2080. Additionally, the German RCM (UHOH-WRF361H) only covers the first 95 years since 1950 and therefore did not qualify for this study. The French RCM (ALADIN53) includes two different temperature units in a single period which is mentioned in the EURO-CORDEX errata table (EURO-CORDEX 2022). However, this problem was adjusted in the algorithm.

Of all eligible ensemble members, three subsets were formed for the analysis. In total, 15 models qualified for RCP4.5, 27 models met the criteria for RCP8.5 but only a limited set of 7 ensemble members provided outputs for *tasmax* and *tasmin* and could therefore be used to calculate the climate indices (Table 2).

Table 1 EURO-CORDEX climate variables, climate statistics and climate indices, derived from climate model data, which were used to identify climate analogue cities

| Climate variables | Climate statistics | Characteristics | Threshold | Weight |
|-------------------|----------------------|--|-----------|--------|
| Temperature | tas_avg (°C) | Annual mean 2-m air temperature | 0.1 °C | 10 |
| | tas_amp (°C) | Annual mean 2-m air temperature amplitude | 1 °C | 1 |
| | tasmax_hot (days) | Annual sum of hot days (≥ 30 °C) | | |
| | tasmax_summer (days) | Annual sum of summer days (≥ 25 °C) | | |
| | tasmin (days) | Annual sum of tropical nights (≥ 20 °C) | | |
| Precipitation | tas_r_pr | Annual mean correlation of 2-m air temperature and precipitation | 0.1 | 10 |
| | pr_sum (mm) | Annual sum of precipitation | 20 mm | 0.05 |
| | pr_amp (mm) | Annual mean precipitation amplitude | 1 mm | 1 |
| | pr_20 (days) | Annual sum of pr20 days (≥ 20 l/m ² precipitation in 6 h) | | |

Table 2 Selected EURO-CORDEX EUR-I1 models, scenarios and variables used for multi-model analysis (ECMWF 2022)

| GCM | RCM | Ensemble Member | | | Scenario | | Variables | | | |
|--------------------------------|---------------------------------|-----------------|---------|----------|----------|--------|-----------|--------|--------|----|
| | | Member | Version | Scenario | RCP4.5 | RCP8.5 | tas | tasmax | tasmin | pr |
| CNRM-CERFACS-CNRM-CM5 (France) | CLMcom-CCLM4-8-17 (Germany) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | CNRM-ALADIN53 (France) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | CNRM-ALADIN63 (France) | r1i1p1 | 2 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | DMI-HIRHAM5 (Denmark) | r1i1p1 | 2 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | IPSL-WRF38IP (France) | r1i1p1 | 2 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | KNMI-RACMO22E (Netherlands) | r1i1p1 | 2 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | RMIB-UGent-ALARO-0 (Belgium) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | CLMcom-CCLM4-8-17 (Germany) | r12i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | DMI-HIRHAM5 (Denmark) | r1i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r3i1p1 | 2 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| ICHEC-EC-EARTH (Ireland) | | r12i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r3i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r12i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| IPSL-IPSL-CM5A-MR (France) | KNMI-RACMO22E (Netherlands) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | r3i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r12i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| IPSL-IPSL-CM5A-MR (France) | IPSL-IPSL-IPSL-WRF38IP (France) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| MPI-M-MPI-ESM-LR (Germany) | CLMcom-CCLM4-8-17 (Germany) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | KNMI-RACMO22E (Netherlands) | r1i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | MPI-CSC-REMO2009 (Germany) | r1i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | r2i1p1 | 1 | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | | r3i1p1 | 1 | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ |
| | GERICS-REMO2015 (Germany) | r3i1p1 | 1 | ✗ | ✓ | ✓ | ✗ | ✓ | ✓ | |

Table 2 (continued)

| GCM | RCM | Ensemble Member | Version | Scenario | | Variables | | | |
|------------------------|-----------------------------|-----------------|---------|----------|--------|-----------|--------|--------|----|
| | | | | RCP4.5 | RCP8.5 | tas | tasmax | tasmin | pr |
| NCC-NorESM1-M (Norway) | DMI-HIRHAM5 (Denmark) | rlilp1 | 2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | | rlilp1 | 3 | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ |
| | GERICS-REMO2015 (Germany) | rlilp1 | 1 | ✗ | ✓ | ✓ | ✗ | ✗ | ✓ |
| | | rlilp1 | 1 | ✗ | ✓ | ✓ | ✗ | ✗ | ✓ |
| | KNMI-RACMO22E (Netherlands) | rlilp1 | 1 | ✗ | ✓ | ✓ | ✗ | ✗ | ✓ |
| | | rlilp1 | 1 | ✗ | ✓ | ✓ | ✗ | ✗ | ✓ |

2.4 Bias adjustment

Raw EURO-CORDEX data needed to be bias-corrected as both climate variables—temperature (underestimation) and precipitation (overestimation)—showed errors in historical data (reference period 1961–1990). To apply local bias adjustment over 389 grid points, reanalysis-driven RCMs were chosen because the datasets have shown to considerably improve spatiotemporal aspects of the raw model (IPCC 2015; Maraun 2016). In January 2020, a reduced version of the 5th generation of European Re-Analysis (ERA5-Land) was published in the C3S CDS, achieving a very high spatial and temporal resolution (9 km; hourly or monthly averaged; Muñoz-Sabater et al. 2021).

Before applying bias correction, reanalysis data for the city of Aachen was quality-assessed by comparing it to actual observed data by the Deutscher Wetterdienst (2021b). The observational data consisted of three weather stations in Aachen, covering time spans of 1951–1979, 1951–2006 and 1891–2011. First, the data of the three weather stations were compared in the overlapping time span between 1951 and 1978 to ensure that similar data series have been produced. After that, monthly averaged precipitation and temperature data from the two longer-running stations were compared to the four nearest ERA5-Land grid points, starting with the year 1981 until the end of the respective stations time series.

As latitudes and longitudes for ERA5-Land proceed in 0.1° steps, four pairs of coordinates were calculated based on a city's coordinate by rounding to the next full tenths value. The nearest pair of coordinates was selected by calculating the shortest Euclidean distance. For cities near the coastline, the longest Euclidean distance was chosen as the nearest pair was predominantly located over sea and therefore not included in the ERA5-Land record.

Finally, the delta change approach proposed by Maraun (2016) based on ERA5-Land data (T_E , P_E) as well as CORDEX temperature T_C and CORDEX precipitation P_C was applied onto the dataset of each ensemble member (T , P) to receive bias-corrected values (T_{BC} , P_{BC}). Both equations are calculated in degrees Celsius.

$$T_{BC} = b * T + a \rightarrow \text{with } a = T_E - T_C; b = 1 \quad (1)$$

$$P_{BC} = a + b * P \rightarrow \text{with } a = 0; b = \frac{P_E}{P_C} \quad (2)$$

2.5 Climate analogue city algorithm

The first step in the algorithm included the already mentioned bias adjustment to tas and pr on a daily basis. Then, five climate statistics were calculated (tas_avg, tas_amp, pr_sum, pr_amp, tas_r_pr) and subjected to nonparametric fitting based on RMSE, since a running mean would lead to data loss at the end of the time span. The result is a curve that minimises the RMSE throughout the time series of the respective variable. The data points of that curve represent the climatic expression of the given variable around each year of the time series. Similar to Rohat et al. (2017), experimentally established thresholds t were defined for each variable. They were then used to calculate weighting factors w (3) (Table 1):

$$w = \frac{1}{t} \quad (3)$$

These weighting factors were used to standardise the values of the five climate variables when finding the climate analogue city. Due to this, a difference of the factor t in each variable results in the same weighted difference. For example, a difference of 0.1 °C in the variable `tas_avg` and 20 mm in the variable `pr_sum`, both result in a weighted difference of 1. For this, we computed for each year of the time span the sum of the weighted difference across all climate parameters j between Aachen (Y) and the remaining 389 cities X_i , including the study area itself. As not every model covers the time span up to the year 2100, 2099 was chosen as the last year.

$$\Delta = \sum_{j=1}^5 \left| (X_{ij} - Y_j) * w_j \right| \quad \forall i \in \{1 \dots, 389\} \quad (4)$$

The analogue city C for a particular year, scenario and model is the one yielding the minimal value Δ . Hence, each model is assigned an analogue city throughout the twenty-first century for every climate scenario. At last, the potential climate analogue cities were compared by their frequency of occurrence as a result, climate statistics and climate indices (hot days, summer days, tropical nights, `pr20`), as the former variables (`tasmax`, `tasmin`) were only available for the smallest ensemble and therefore not applicable in the climate city analogue algorithm. Additionally, a 30-year running mean (2069–2099) was chosen to represent Aachen's future climate indices since nonparametric fitting based on RMSE proved less accurate.

3 Results and discussion

In this section, the findings are presented and thereafter discussed and interpreted in the subsections. Table 3 and the map in Fig. 1 illustrate the results found by the algorithm. The analogue cities are spread across multiple countries for both scenarios but show a distinctive pattern mostly south, west or southwest of Aachen, which follows the southward shift found by Beniston (2014) and Rohat et al. (2017). With the exception of the Italian analogues and Toulouse, all cities were found in areas currently classified as Cfb (warm and humid with warm summers) in the Köppen–Geiger climate classification. However, 10 out of 18 lie within or in direct vicinity of Cfa (warm and humid with hot summers), Csa (warm and summer dry with hot summers) or Csb (warm and summer dry with warm summers) climates.

3.1 RCP4.5

Out of 15 results, 9 climate twins were computed, with the city of Dijon occurring five times and thus most often. However, some EURO-CORDEX models report decreases in temperatures during the second half of the century. For example, the German MPI-M-MPI-ESM-LR MPI-CSC-REMO2009 r2i1p1 revealed the city of Dijon as a climate twin by the year 2075 before significantly dropping in temperature and changing its geographic shift to follow a path northward. This represents an important detail which should not go unnoticed as maximum temperature is of interest and significance for, e.g., spatial planners. The north–south distance covered between Aachen and Dijon is 380 km which fits the range of a northward shift of isotherms by 2 to 14 km per year, in agreement with estimates by Beniston (2014). Further results included cities further south than Dijon, in particular Limoges (550 km), Pamplona (1060 km) and Vitoria-Gasteiz (1100 km). Both Spanish cities

Table 3 Aachen's climate analogue cities by the end of the twenty-first century for selected EURO-CORDEX models. Abbreviations in brackets refer to the geographical location. The first letter indicates relative positioning within a country (N=North, S=South, E=East, W=West, C=Central) whereas the second letter describes the country itself (E=England, F=France, G=Germany, I=Italy, N=Netherlands, S=Spain)

| GCM | RCM | | Scenario | |
|----------------------------|--------------------------------|------------------------------|----------------------|---------------|
| | CNRM-CERFACS-CNRM-CM5 (France) | CLMcom-CCLM4-8-17 (Germany) | RCP4.5 | RCP8.5 |
| ICHEC-EC-EARTH (Ireland) | CNRM-ALADIN53 (France) | CNRM-ALADIN63 (France) | Dijon (CF) | Prato (NI) |
| | DMI-HIRHAM5 (Denmark) | DMI-HIRHAM5 (Denmark) | Le Havre (NF) | Venice (NI) |
| | IPSL-WRF381P (France) | IPSL-WRF381P (France) | ✗ | Florence (NI) |
| | KNMI-RACMO22E (Netherlands) | KNMI-RACMO22E (Netherlands) | ✗ | Florence (NI) |
| | RMIB-UGent-ALARO-0 (Belgium) | RMIB-UGent-ALARO-0 (Belgium) | ✗ | Prato (NI) |
| | CLMcom-CCLM4-8-17 (Germany) | CLMcom-CCLM4-8-17 (Germany) | Dijon (CF) | Florence (NI) |
| | DMI-HIRHAM5 (Denmark) | DMI-HIRHAM5 (Denmark) | Dijon (CF) | Bordeaux (WF) |
| | | | ✗ | Bordeaux (WF) |
| | | | Neuss (WG) | Bordeaux (WF) |
| | | | ✗ | Toulouse (SF) |
| IPSL-IPSL-CM5A-MR (France) | KNMI-RACMO22E (Netherlands) | KNMI-RACMO22E (Netherlands) | Pamplona (NS) | Florence (NI) |
| | | | ✗ | Florence (NI) |
| | | | Vitoria-Gasteiz (NS) | Bordeaux (WF) |
| | | | Den Haag (NN) | Brescia (NI) |
| | | | Dijon (CF) | Bilbao (NS) |
| | | | ✗ | Prato (NI) |
| | | | Bournemouth (SE) | Lorient (WF) |
| | | | ✗ | Lorient (WF) |
| | | | Vitoria-Gasteiz (NS) | Lyon (CF) |
| | | | Oberhausen (WG) | Lyon (CF) |
| | | ✗ | Florence (NI) | |
| MPI-M-MPI-ESM-LR (Germany) | | | | |
| | | | | |
| IPSL-IPSL-CM5A-MR (France) | | | | |
| | | | | |
| IPSL-IPSL-CM5A-MR (France) | | | | |
| | | | | |
| MPI-M-MPI-ESM-LR (Germany) | | | | |
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| IPSL-IPSL-CM5A-MR (France) | | | | |
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Table 3 (continued)

| GCM | RCM | Scenario | |
|------------------------|-----------------------------|------------|---------------|
| | | RCP4.5 | RCP8.5 |
| NCC-NorESM1-M (Norway) | DMI-HIRHAM5 (Denmark) | rii1pl v.2 | Lorient (WF) |
| | | rii1pl v.3 | Florence (NI) |
| | GERICS-REMO2015 (Germany) | | Prato (NI) |
| | IPSL-WRF38IP (France) | | Prato (NI) |
| | KNMI-RACMO22E (Netherlands) | | Prato (NI) |
| | | | Prato (NI) |

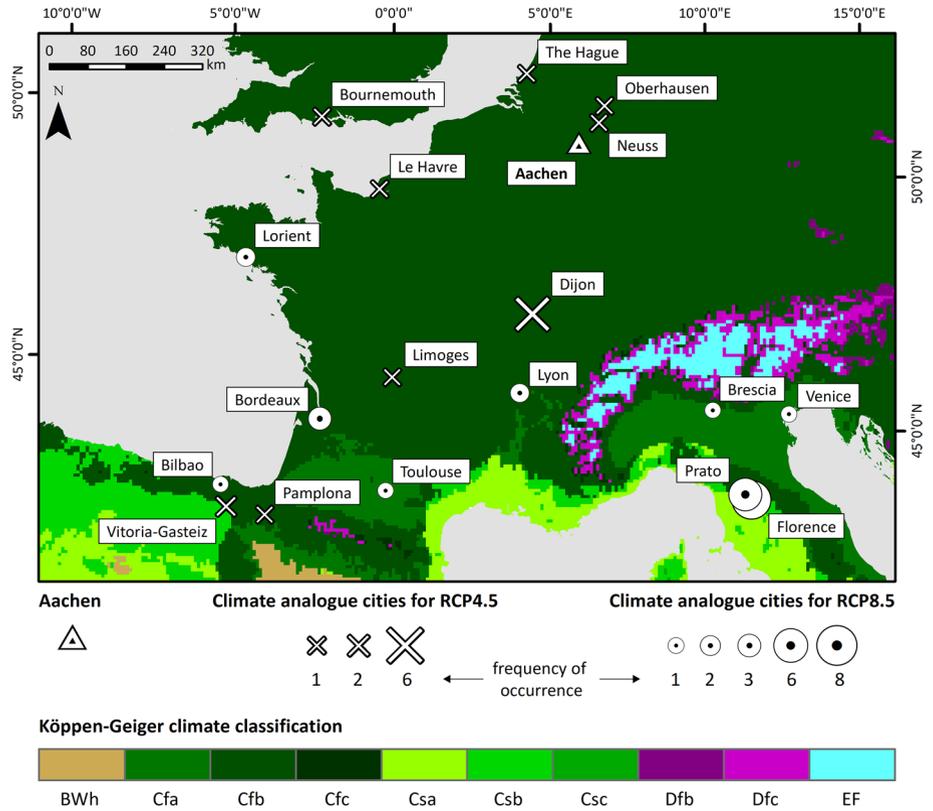


Fig. 1 Climate analogue cities of Aachen for RCP4.5 and RCP8.5 and present Köppen–Geiger climate classification after Kottek et al. (2006). The size of the symbols refers to the number of RCMs for which the algorithm has returned the respective city as a climate analogue for Aachen (frequency of occurrence). Coastline data was provided by Natural Earth (2022)

marginally meet those conditions. On the other hand, Le Havre, Den Haag, Bournemouth and two nearby German cities (Oberhausen, Neuss) reflect a contrary trend, which can be explained through a decrease in temperature in the second half of the twenty-first century.

Boxplots and climate indices were computed to further analyse and explain these results (Fig. 2, Table 4).

Small interquartile ranges are found for the annual average 2-m air temperature as well as for the precipitation sum, whereas higher values are found for amplitudes and correlation. Oberhausen, Neuss and Den Haag were selected by the algorithm as they fit well with precipitation amplitude, correlation and temperature amplitude even though they perform low on annual average air temperature and only partially fit average annual precipitation sums. Also, due to their location and altitude, close-by Oberhausen and Neuss show large similarities for all temperature indices and pr20. Bournemouth performs similarly for subplot pr_amp but shows lowest values for precipitation sum and temperature amplitude.

The Spanish cities Vitoria–Gasteiz and Pamplona show comparable tendencies because of their geographic proximity but slight changes in average temperature and precipitation sum. Overall, they can be characterised as too hot and too dry as their averages on summer

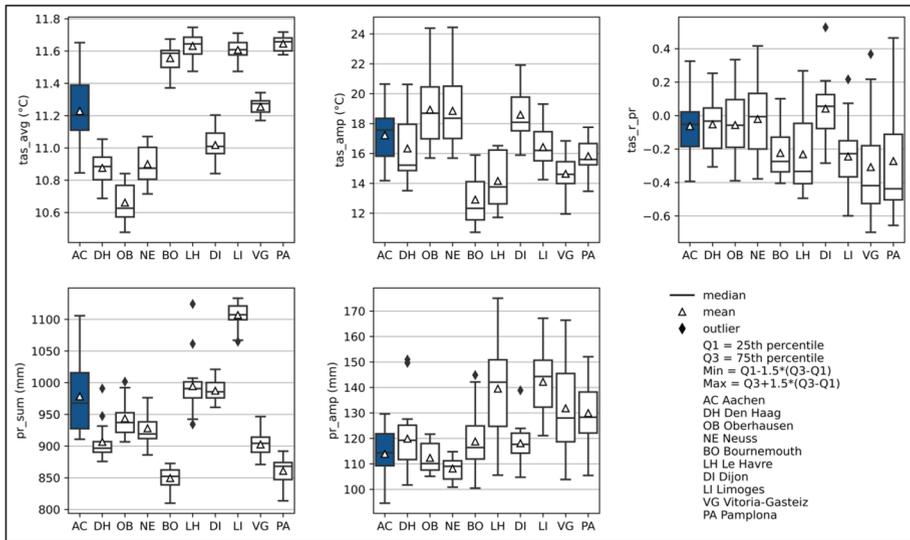


Fig. 2 Boxplots describing climate statistics from Table 1 (number of ensemble members = 15) for every possible climate analogue city of Aachen (ordered by latitude) for RCP4.5 (2099)

Table 4 Climate indices from Table 1 (number of ensemble members = 7) for every possible climate analogue city of Aachen (2069–2099) for RCP4.5

| RCP4.5 | | AC | BO | DI | LH | LI | PA | VG | DH | OB | NE |
|-----------------|---------|-------|------|-------|------|-------|-------|-------|------|-------|-------|
| Summer days | Average | 31 | 8 | 39 | 15 | 38 | 48 | 39 | 19 | 34 | 36 |
| | Range | 17–51 | 0–27 | 21–57 | 5–26 | 22–55 | 25–61 | 17–51 | 8–33 | 16–54 | 18–56 |
| Hot days | Average | 6 | 1 | 8 | 2 | 8 | 14 | 11 | 4 | 8 | 8 |
| | Range | 1–11 | 0–4 | 1–14 | 0–6 | 2–14 | 4–21 | 2–17 | 1–9 | 2–17 | 2–17 |
| Tropical nights | Average | 6 | 2 | 5 | 3 | 4 | 3 | 2 | 3 | 6 | 5 |
| | Range | 1–17 | 0–6 | 1–12 | 0–10 | 1–10 | 0–7 | 0–6 | 0–13 | 1–22 | 1–15 |
| pr20 | Average | 3 | 3 | 5 | 4 | 6 | 5 | 4 | 3 | 3 | 3 |
| | Range | 2–6 | 1–4 | 2–7 | 1–6 | 2–10 | 2–6 | 2–6 | 1–4 | 2–5 | 2–5 |

days surpass Aachen’s amount by about a third to a half, and show twice as many hot days. They are therefore not likely to become climate analogues even if Vitoria–Gasteiz was surprisingly close to Aachen with only one more pr20 event per year. Le Havre fits well for precipitation sums and pr20 events, but shows significantly fewer summer days, hot days or tropical nights because of its lower temperature amplitude resulting from the sea climate. Limoges only partially indicates good overlap with Aachen’s future climate, as the cities’ climate can be described as too hot and too wet. Dijon displays the highest similarities by fitting very well in four out of five subplots. The city also nearly matches climate indices with only a slightly higher number in summer days (+8) and nearly identical amounts of hot days (+2), tropical nights (–1) and pr20 events (+2).

These findings challenge Bastin et al. (2019) who state that the city of London, comparable in climate to the city of Aachen, ‘will be more similar to Barcelona’ than to London’s present climate already by 2050 for RCP4.5.

3.2 RCP8.5

The larger ensemble of 27 models produces, as expected, higher overall ranges for each climate statistic (Fig. 3). Here also, 9 potential climate analogues were found (Fig. 3, Table 3). Italian analogues (Brescia, Florence, Prato, Venice) were computed 16 times, twice as much as French cities (Bordeaux, Lorient, Lyon, Toulouse). Spanish analogues are represented by only a single city (Bilbao).

Lyon and Lorient both reveal low air temperatures that characterise the cities as too cold for an RCP8.5 analogue but too hot for scenario RCP4.5 (Fig. 2, Fig. 3). Consequently, these results might reflect scenario RCP6.0, which we could not examine directly (see methods). However, precipitation shows better results, which is why these cities were selected by the algorithm. The cities differ in climate indices, which can be explained through the maritime location of Lorient compared to the continental climate of Lyon. Lyon exceeds Aachen in the number of summer and hot days as well as pr20 events, whereas Lorient shows very low results in all categories (Table 5).

Prato and Florence show very similar behaviour in all five climate statistics because both cities are separated by a very short distance of only about 15 km. Therefore, these analogues can be treated similarly. Even though they display analogous results for air temperature and precipitation sum, both amplitudes are significantly increased, leading to a tripling or nearly quadrupling of hot days and a doubling of summer days compared to Aachen. Tropical nights are increased by 50% and pr20 events by more than 100%. Similar conditions applied to Brescia and Venice, raising the debate whether temperature indices should by all means be included in the algorithm, as these Italian analogues can be rated too hot. Unfortunately, these calculations are only possible with seven of the selected models. Providing these variables (tasmax and tasmin) for a bigger ensemble could therefore increase the algorithm’s effectiveness. The Spanish coastal city of Bilbao also does not meet all the expectations to qualify as an analogue for Aachen as temperature amplitude

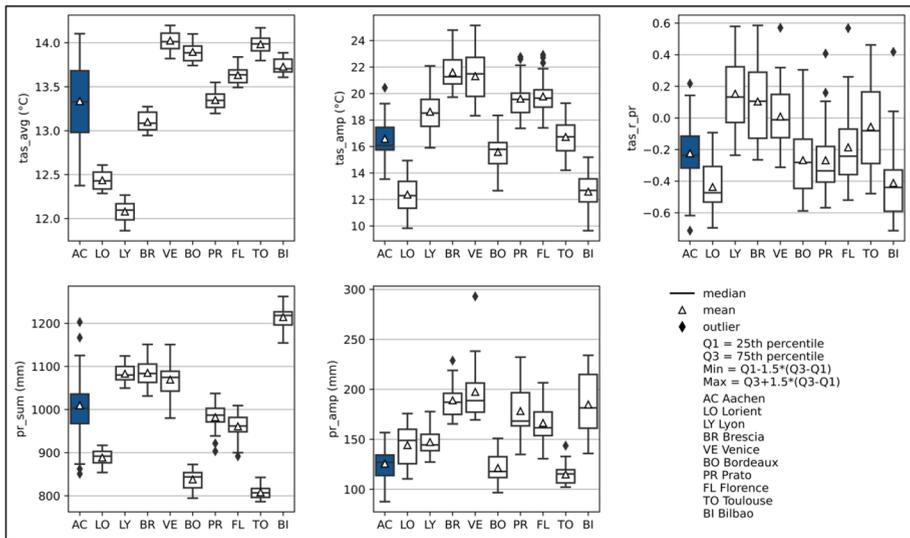


Fig. 3 Boxplots describing climate statistics from Table 1 (number of ensemble members = 27) for every possible climate analogue city of Aachen (ordered by latitude) for RCP8.5 (2099)

Table 5 Climate indices from Table 1 (number of ensemble members=7) for every possible climate analogue city of Aachen (2069–2099) for RCP8.5

| RCP8.5 | | AC | BI | BO | BR | FL | LO | LY | PR | TO | VE |
|-----------------|---------|-------|-------|-------|--------|--------|------|-------|--------|-------|--------|
| Summer days | Average | 41 | 48 | 64 | 84 | 94 | 18 | 56 | 88 | 74 | 87 |
| | Range | 25–67 | 25–63 | 43–79 | 69–104 | 79–115 | 6–38 | 37–72 | 74–111 | 55–90 | 68–109 |
| Hot days | Average | 10 | 14 | 20 | 23 | 37 | 2 | 16 | 31 | 25 | 23 |
| | Range | 2–16 | 3–20 | 6–28 | 9–36 | 15–57 | 0–8 | 4–23 | 11–54 | 10–36 | 4–36 |
| Tropical nights | Average | 11 | 7 | 12 | 24 | 17 | 3 | 8 | 16 | 16 | 38 |
| | Range | 3–23 | 2–15 | 5–21 | 11–37 | 4–27 | 0–9 | 3–16 | 4–33 | 10–26 | 21–55 |
| pr20 | Average | 4 | 10 | 3 | 13 | 9 | 4 | 9 | 10 | 4 | 13 |
| | Range | 3–6 | 6–15 | 1–7 | 7–16 | 3–13 | 1–7 | 5–11 | 5–14 | 1–6 | 11–16 |

shows low values while precipitation sum and amplitude exceed significantly. However, climate indices fit best among all possible analogues for summer and hot days. Last, Bordeaux and Toulouse are discussed together as both cities reveal identical patterns. Both cities perform well for *tas_amp* and *pr_amp* but are generally slightly too hot and too dry to reflect the possible future climates of Aachen. This leads to increased summer and hot days. However, both cities show nearly identical amounts of *pr20* events and Bordeaux even reflects almost equal amounts of tropical nights.

To sum up, there is no clear European climate analogue city of Aachen for scenario RCP8.5. Bilbao fits best regarding temperature but not for precipitation indices, which are covered by Bordeaux and Toulouse. Rohat et al. (2017) determined that Cologne, located 60 km east of Aachen, is the climate twin of Bordeaux for the SRES A2 (2071–2100), which is comparable to RCP8.5. Also, Toulouse is considered to be the climate analogue of Düsseldorf which is located at a distance of 70 km to Aachen (Landeshauptstadt Düsseldorf 2020). Additionally, Fitzpatrick and Dunn (2019) computed that geographic distances between study areas and climate analogue regions are ‘nearly twice as large for RCP8.5 [...] as compared to RCP4.5 [...]’. Considering that this fits the relation of the north–south distance between Aachen and Dijon (380 km) for RCP4.5 and Aachen and Bordeaux (660 km) and Toulouse (800 km) for RCP8.5, Aachen might have a non-urban climate twin within the city triangle Bordeaux–Toulouse–Bilbao. Alternatively, it could enter a novel climate, i.e., a combination of temperature and precipitation related variables poorly represented by any presently existing location.

3.3 Limitations and added value to existing studies

The limitations of this study are attributable to the data and methodology that build on the type, the scope as well as the temporal and spatial resolution. Some models had to be excluded from the data sample because they use a different calendar system, do not cover the entire study period or do not display necessary variables or scenarios. It is also unclear to what extent the RCMs can represent a city’s unique climate. Effects, concerning the differences between a city and its surroundings, such as the UHI, are represented in many models through the so-called ‘bulk’ scheme, where cities are treated like rock surfaces (Langendijk et al. 2019; Karlický et al. 2020).

However, this approach is unable to predict the climatic processes within a more realistic urban setting where vegetated spaces play a major role (Langendijk et al. 2019). A comparison between an actual urban climate and its climate analogue seems therefore not possible. In addition, a city's climate signal generated by the 'bulk' scheme might be weakened due to the calculation of the spatial average of the four closest grid cells to a city, especially for smaller cities like Aachen. Furthermore, bias adjustment was needed but cannot 'overcome fundamental misspecifications of a climate model' (Maraun 2016). Additionally, scenario RCP8.5 has shown that an underestimation of the temperature amplitude threshold can turn out in an overestimation of hot and summer days as well as tropical nights, leading to unrealistic climate analogue city results. Unfortunately, an implementation of climate indices was not possible as not enough data were available at that time. However, in accordance with Rohat et al. (2017), it was shown that climate indices provide an important measure when determining climate analogue cities and should be taken into consideration. As results of the scenario RCP8.5 were showing no suitable climate twin, an adaptation of the benchmark for the definition of a city or the consideration of data from other continents could resolve this problem. Even then, it needs to be pointed out that topography and orography of the reference city and its climate twin have to be taken into account for the implementation of climate adaptation strategies through the study of analogues. It is also important to consider that climate twins are determined for a specific point in time and the change of climate in a reference city can be seen as a 'track' throughout the century.

This study combines several approaches to determine climate analogue cities. In accordance with Fitzpatrick and Dunn (2019) and Rohat et al. (2018), we used a large model ensemble but a novel approach to define the most likely twin city. Instead of computing a multi-model mean, we computed a single analogue city for each climate simulation and analysed the frequency of occurrence of each possible city throughout the ensemble. The city selected by the largest number of simulations is defined as the most likely climate twin. With this approach, we visualise the diverse range of possible analogues in a multi-model ensemble, which was noticed but not shown by Rohat et al. (2017). Since most previous studies focused on a sample of major cities (Bastin et al. 2019; Hallegatte et al. 2007; Kopf et al. 2008; Rohat et al. 2018), we put our focus on a typical mid-sized, mid-European urban area and used a dataset of 389 cities, also including those with 150,000 to 200,000 inhabitants, which has, to our knowledge, not been previously applied for Europe. With our focus on a single city, we additionally showed an approach that is much more likely to be applied by planning departments of individual urban communities, who might be interested in detailed possible scenarios for their own city rather than great amounts of data with information on others.

4 Conclusion and outlook

This study focused on a methodology to derive climate analogue cities for spatially highly resolved future climate scenarios using five statistical climate variables on the exemplary city of Aachen (Germany). The developed algorithm can be applied to any of the cities included in the dataset which adds flexibility and extends the study areas. The underlying motivation emerged from the need to 'raise the population's awareness about the pace and

the expected impacts of climate change' through the Climate Twins approach as well as to assist decision-making in city planning (Rohat et al. 2017). Urban-scale studies can help specify mitigation and adaptation frameworks to strengthen the resilience and recovery of cities in the future.

In this case, we found that the French city of Dijon is highly likely to become Aachen's climate twin by the end of the century for RCP4.5. As for the scenario RCP8.5, no clear European analogue city could be determined, indicating that the city might probably enter a novel climate. The nearest matches suggest the encompassing region of the French–Spanish city triangle Bordeaux–Toulouse–Bilbao. However, a better matching analogue city might be found outside the model domain since this result may originate from spatial limitation (Hallegatte et al. 2007). Alternatively, some authors proposed to couple twin climate cities based on particular climate impacts, e.g., heat waves, droughts or heavy precipitation (Rohat et al. 2017). Consequently, one could argue that Bordeaux and Toulouse reflect Aachen's heavy precipitation twins whereas Bilbao fits as a temperature index twin. While this standpoint gathers some advantages, it should not be lost sight of the fact that there still is a necessity to include temperature indices in climate analogue city research to ensure a more holistic algorithm that can cover these aspects of heat waves. Despite the limitations mentioned above, we presented an application-oriented method which provides realistic and detailed results for a typical mid-sized city, is applicable for a large number of urban areas and expandable with additional RCM data.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Lynn Reuter. The first draft of the manuscript was written by Lynn Reuter, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The Urban Audit data used to create the set of possible climate analogue regions are available from Eurostat, <https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/urban-audit>. The ESPON population census data used to create the set of possible climate analogue regions are available from ESPON Database Portal, <https://database.espon.eu/indicator/1260/#metadata-download>. The CORDEX regional climate model data are available from the Copernicus Climate Data Store, <https://doi.org/10.24381/cds.bc91cdc3>. The hourly/monthly ERA5-Land data used for bias correction of the CORDEX regional climate model data are available from the Copernicus Climate Data Store, <https://doi.org/10.24381/cds.e2161bac>. The climate data for Aachen used for validation of the ERA5-Land data are available from the Climate Data Center of the Deutscher Wetterdienst (DWD), https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/historical/. The Köppen-Geiger climate classification data with proposed colouring of the classes in Fig. 1 are available from <http://koeppen-geiger.vu-wien.ac.at/present.htm>. Coastline data in Fig. 1 is available from the Natural Earth website, <https://www.naturalearthdata.com/downloads/10m-physical-vectors/10m-ocean/>. The climate analogue city algorithm of this study is available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All authors gave explicit consent to submit the manuscript and obtained consent from the responsible authorities at the institute/organisation where the work has been carried out.

Competing interests The authors declare no competing interests.

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