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# Characterization of European cities' climate shift – an exploratory study based on climate analogues

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## Abstract

**Purpose** – Climate analogues have been extensively used in ecological studies to assess the shift of ecoregions due to climate change and the associated impacts on species survival and displacement, but they have hardly been applied to urban areas and their climate shift. This paper aims to use climate analogues to characterize the climate shift of cities and to explore its implications as well as potential applications of this approach.

**Design/methodology/approach** – The authors propose a methodology to match the current climate of cities with the future climate of other locations and to characterize cities' climate shift velocity. Employing a sample of 90 European cities, the authors demonstrate the applicability of this method and characterize their climate shift from 1951 to 2100.

**Findings** – Results show that cities' climate shift follows rather strictly north-to-south transects over the European continent and that the average southward velocity is expected to double throughout the twenty-first century. These rapid shifts will have direct implications for urban infrastructure, risk management and public health services.

**Originality/value** – These findings appear to be potentially useful for raising awareness of stakeholders and urban dwellers about the pace, magnitude and dynamics of climate change, supporting identification of



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the future climate impacts and vulnerabilities and implementation of readily available adaptation options, and strengthening cities' cooperation within climate-related networks.

**Keywords** Awareness-raising, Climate analogues, Climate shift, Climate velocity, Urban adaptation

**Paper type** Research paper



## 1. Introduction

It is by now widely acknowledged that climate change will pose significant threats to both urban systems and city dwellers (Bulkeley, 2013). Because urban areas hold more than half of the world's population and most of people's assets, it is of utmost importance to define adequate adaptation strategies (Lee and Lee, 2016). Their strict implementation at the urban level is supposed to significantly reduce the inhabitants' vulnerability to climate change and ensure the quality of life for future generations. Nevertheless, despite an overwhelming scientific evidence of increasing climatic threats, urban adaptation strategies are more often absent than present, even in countries of the global North. Although a certain number of cities self-reported to be actively engaged in climate adaptation and mitigation at the local scale (Aylett, 2015), Reckien *et al.* (2013) found that 72 per cent of 200 European major cities have not yet implemented a climate adaptation plan. Such lack of political commitment is explained by numerous factors (Juhola, 2016), including insufficient funding, time-scale mismatches between political mandate and climate change (Bicknell *et al.*, 2009; Hallegatte, 2009), underlying uncertainties of climate projections (Schneider, 2006) and misunderstanding of the forthcoming climate impacts (Van der Linden *et al.*, 2014). Moreover, among the great number of factors identified as drivers of urban adaptation planning (Reckien *et al.*, 2015), efficient and easy-to-understand scientific information and knowledge (Archie *et al.*, 2014; Mycoo, 2015), involvement in climate-related cities' networks and strong community engagement (Bulkeley *et al.*, 2011) are identified to play an important role. Consequently, there is a growing need of new and innovative methods that: (i) raise urban residents and stakeholders' awareness about the potential impacts of climate change; (ii) provide easily understandable scientific information about the future impacts and adequate adaptation options; (iii) foster cities' collaboration within climate-related networks.

The climate analogues approach has the potential to address this need. This method – also known as the "climate twins approach" (Ungar *et al.*, 2011) – is designed to match the future (or past) climate of a given location with the current climate of another location. This way, a pair of climate analogues is made of two different geographical locations sharing a significantly similar climate for a different time period. Such approach has been initially developed in the field of ecological studies, with the purpose of investigating climate change impacts on the shift of ecological communities and species habitat and the appearance of novel climate and ecoregions (Saxon *et al.*, 2005; Peacock and Worner, 2006; Williams and Jackson, 2007, Veloz *et al.*, 2012a, 2012b), as well as the implications of such shift for species' survival and abundance (Anderson *et al.*, 2013; Leibing *et al.*, 2013). Climate analogues have also been used in agricultural studies to identify potential cultivars better suited to future climatic conditions (Webb *et al.*, 2013) and to investigate adaptation solutions existing today, based on the assumption that the future of one farmer is similar to the present of another one, located in a different region (Ramirez-Villegas *et al.*, 2011).

This approach has also shown a great potential for raising awareness about the magnitude and pace of climate change. For instance, Ungar *et al.* (2011), CSIRO-Bureau of Meteorology (2016) and Rohat *et al.* (2016) developed user-friendly climate analogue tools which provide an intuitive visualization of potential climate change impacts. In the same line, Kopf *et al.* (2008) and Climate Communication (2014) used climate analogues to communicate about the amplitude of climate change to a lay audience, whereas Beniston (2013) matched the past and current climates to provide easy-to-understand information about the celerity of climate change in the past decades.

However, the application of this approach in urban areas has largely been underused so far. The few climate analogues studies focusing on cities have shown that climate analogues can help assessing economic damages of climate change (Hallegatte *et al.*, 2007) and identifying both adequate adaptation policies (Kellett *et al.*, 2011) and best practices of climate adaptation (Rohat *et al.*, 2016). Nevertheless, none of these studies used climate analogues to characterize the velocity of cities' future climate shift – i.e. the speed and orientation of the geographical displacement over time – and to explore its potential implications on urban dwellers and on the design of adaptation strategies.

In this interdisciplinary effort, we propose a climate-matching method that reliably matches the current and future climates of any location worldwide, and we show how it can be used to assess the associated shift velocity. Employing a large sample – 90 different cities – we exemplify the applicability of this method and characterize the climate shift of European cities from 1951 to 2100. We then discuss the potential implications of such cities' climate shift and provide insights into the possible use of the proposed approach, e.g. for raising awareness of both city dwellers and decision-makers about the pace, magnitude, and dynamics of climate change, for supporting the identification and implementation of adequate adaptation strategies, and for enhancing cities' cooperation within transnational climate-related networks.

## 2. Methods and materials

### *2.1 Climate-matching approach*

In the past few years, two main methods to match one climate with another have been described. One is based on the aggregation of different climate statistics within a similarity index – e.g. the CCAFS index (Climate Change, Agriculture and Food Security; Ramirez-Villegas *et al.*, 2011; Leibing *et al.*, 2013) or a simpler index using the standardized Euclidean distances (SEDs) (Williams and Jackson, 2007; Veloz *et al.*, 2012a) – whereas the other is based on a comparison between a set of univariate climatic criteria and a set of arbitrarily established thresholds (Hallegatte *et al.*, 2007; Ungar *et al.*, 2011; Rohat *et al.*, 2016). While the latter allows an easy control of the climate analogues' quality – in terms of climatic proximity – the use of a similarity index allows ranking them and hence identifying the climatically closest one. Nevertheless, Grenier *et al.* (2013) showed that the uncertainty associated with the choice of climate models and scenarios is largely superior to the variation resulting from the use of different climate-matching approaches.

In this study, we applied a combination of the two foregoing methods to:

(1) match the climate of any location of interest (LOI) with other locations sharing similar climate – but at a different time period – which we named the LOI's climate analogues; and

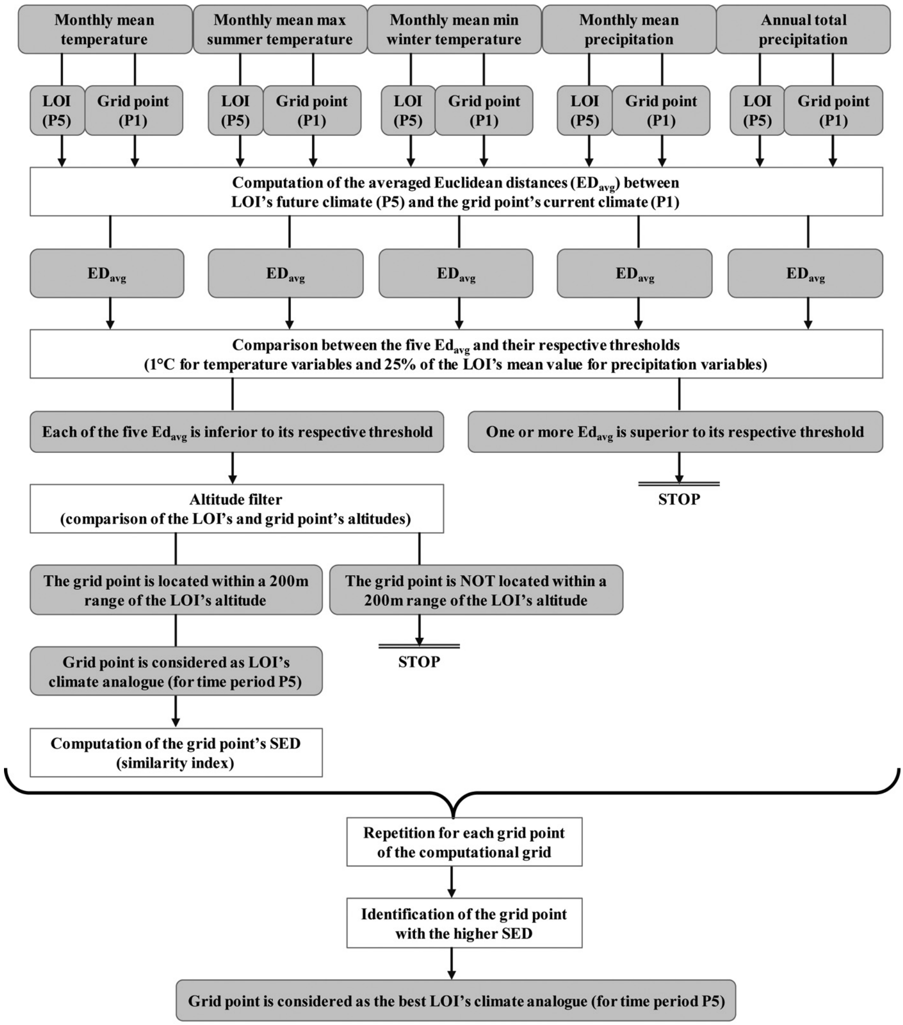
(2) determine the best climate analogue – i.e. the one sharing the most similar climate – for a given LOI and time period.

Although climate has been traditionally characterized by a specific combination of various variables (IPCC, 2001), matching one climate with another requires relaxing this definition. Because the climate-matching method developed in this study is used to investigate cities' climate shift, we took into account climate variables that both represent the overall climate and have a major influence on the functioning of urban areas. Trade-offs have to be made between including the numerous climatic variables that determine a city's climate and keeping low the number of climatic variables to identify a substantial number of climate analogues. This led us to select the five following quantities: monthly mean temperature and monthly mean precipitation, which are the two most essential climatic determinants (Holdridge, 1947); monthly minimal temperature for winter months (December, January and February) and monthly maximal temperature for summer months (June, July and August), which are, respectively, the indicators of cold and warm spells (Ungar *et al.*, 2011); and annual total precipitation, which is an important climatic factor for water management in cities (Hallegatte *et al.*, 2007). These variables were computed monthly (or annually in case of the annual total precipitation variable) and averaged over five 30-year periods, namely, P1 (1951-1980), P2 (1981-2010), P3 (2011-2040), P4 (2041-2070) and P5 (2071-2100).

To identify the climate analogues of a given LOI and time period, we first computed and averaged (as per grid points in the computational domain) the Euclidean distances between the LOI's current climate (P1) and the future climate (P2, P3, P4 or P5) of all the grid points, for the five climatic variables (methodology available as Appendix). Second, we compared the averaged Euclidean distances (five per grid points) with specific thresholds. We arbitrarily fixed these thresholds at 1°C for the three temperature variables and 25 per cent of the LOI's mean value (over the reference time period) for the two precipitation variables. If the averaged Euclidean distances for the five climate variables are under their respective thresholds, then the grid point's future climate is considered as similar to the current LOI's climate. Third, we applied an altitude filter to select the grid points that are located within a 200-meter range (above or below) of the LOI's altitude. Although applying such altitude filter is uncommon in climate analogues studies (Hallegatte *et al.*, 2007; Beniston, 2014), we argue here that it enables a more precise computation of the velocity of latitudinal climate shifts (Section 2.4). The remaining grid points – i.e. those which share significantly similar climate to the LOI and which have passed through the altitude filter – are considered as the LOI's climate analogues (for a given future time period). Finally, we computed their similarity index based on an unweighted SED metric (Appendix) and ranked those to identify the best one, in terms of climatic proximity. Such workflow (Figure 1) is repeated for every LOI and for each of the four 30-year time periods (i.e. P2, P3, P4 and P5).

### *2.2 Climatic data*

Data sets for the case study presented in this paper were extracted from the European project ENSEMBLES (2009), which provides daily values at a horizontal grid-spacing of 25 km, from 1951 to 2100, under the A1B scenario of Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change. To reduce the uncertainties associated with the use of a single regional climate model (RCM), we computed multimodel means of the five climatic variables used in the climate-matching method. Climatic projections originated from seven different RCMs, namely, CNRM-RM4.5 (CNRM, 2008), KNMI-RACMO2 (van Meijgaard *et al.*, 2008), OURANOS-MRCC4.2.1 (Plummer *et al.*, 2006), SMHI-RCA3 (Kjellström *et al.*, 2005), DMI-HIRHAM5 (Christensen *et al.*, 2007), GKSS-CCLM4.8 (Böhm *et al.*, 2006) and METEO-HC-HadRMQ0 (Collins *et al.*, 2006). The five climatic variables were computed monthly (and annually for the variable of annual total precipitation) for the five 30-year periods and for all the grid points (32,300 in total) of the 25-km grid-spacing computational domain.




**Note:** Here, climate shift from P1 to P5 as an example

**Figure 1.**
Schema of the workflow that has been applied to identify the best – in terms of climatic proximity – climate analogue of each LOI, for each shift time period

*2.3 Transects*

According to studies applying the Köppen climate classification in Europe (de Castro *et al.*, 2007; Gerstengarbe and Werner, 2008), the European historical climate is represented by a temperate climate in Western Europe, a continental climate in Eastern Europe and a subtropical climate in the Southern part. Jylhä *et al.* (2010) recently showed that European climates tend to move northeastwards. In this study, there is no attempt to assess the shift of European climatic zones, but rather the positional shift – mainly southwards – of European cities' climate. Beniston (2013) showed that European isotherms have been moving northwards in the past decades, along several north-to-south transects. In the same line and following the existing studies assessing the European climate shift (Jylhä *et al.*, 2010; Beniston, 2013, 2014, 2015), we developed three north-to-south transects, namely an Eastern Europe transect, a Continental transect, and a Maritime transect (Figure 2). These allow investigating the potential differences of climate shift over the European continent. Each of these is made of 30 different cities that have been chosen with regard to both their geographical location (proximity with a selected transect and distance with other cities) and regional importance (size of the population and administrative role). Overall, these 90 cities (Appendix Table AI) are located across 22 European countries, are distributed within several climatic zones, and host approximately 416 million inhabitants, i.e. more than half of the European population (Eurostat, 2012).

### *2.4 Southward velocity*

To assess the southward climate shift velocity – i.e. the speed (in kilometres per year) of the expected southward positional change – of each city of the three transects, we first

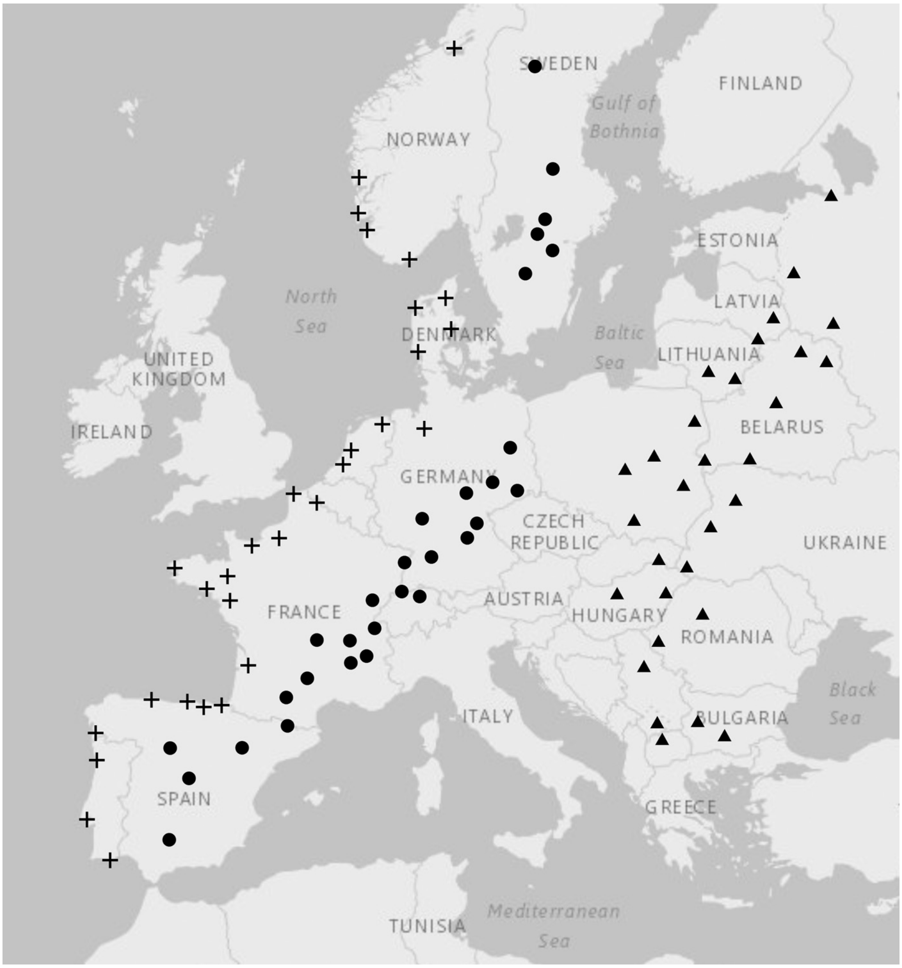



**Figure 2.**
Map displaying the location of the 90 cities forming the three north-to-south transects, namely, Maritime transect (+), Continental transect (•) and Eastern Europe transect (▲)

computed the latitudinal distance between the city and its best climate analogue (for each 30-year time period), using the Haversine formula (Sinnott, 1984). We then divided the latitudinal distance by the number of years between the reference period and the projected period, which can vary from 30 years up to 120 years. Applying this method, we estimated the southward velocity of every city's climate shift for the seven following shifts:

(1) P1-P2: From 1951-1980 to 1981-2010 (30-year shift).
(2) P2-P3: From 1981-2010 to 2011-2040 (30-year shift).
(3) P3-P4: From 2011-2040 to 2041-2070 (30-year shift).
(4) P4-P5: From 2041-2070 to 2071-2100 (30-year shift).
(5) P1-P3: From 1951-1980 to 2011-2040 (60-year shift).
(6) P3-P5: From 2011-2040 to 2071-2100 (60-year shift).
(7) P1-P5: From 1951-1980 to 2071-2100 (120-year shift).

## 3. Results

### *3.1 Applicability of the method*

Out of the 360 different attempts (90 cities and four future 30-year time periods) to identify a climate analogue, 304 were successful (success rate of 84 per cent), highlighting the applicability of this method over the European continent. Among the 90 investigated cities, 70 cities were found to have reliable climate analogues for each of the four 30-year future time periods. For the other 20 cities, no climate analogue was found for at least one future time period. Among them, two cities, namely Geneva (Switzerland) and Sofia (Bulgaria), did not have any climate analogues for the four future time periods. Most of these 20 cities are located at the edge of the European domain; hence their respective climate analogues are presumably located outside Europe. For instance, climate analogues of the cities located in the Iberian Peninsula (extreme south of the computational grid), e.g. Vigo (Spain), Faro (Portugal), and Porto (Portugal), are presumably located in North Africa. However, for other cities such as Geneva (Switzerland), no climate analogue was found simply because its future climate does not currently exist in Europe. This may be because of the appearance of novel climates in a changing climate context (Williams and Jackson, 2007).

### *3.2 Direction of shifts*

Results showed that climate analogues are always located southwards of their respective city of reference. This rather expected result highlights the well-known equator-ward displacement of the climatic zones (i.e. from north to south in case of Europe). One of the added values of the method as applied here lies in the identification of transects of climate shift. To assess whether or not European cities' climate shift follows the three predetermined transects, we computed the longitudinal distance between each climate analogue and their reference transect (Maritime, Continental, or Eastern Europe). Results showed that the longitudinal distance between climate analogues and their reference transect ranges from 0 to 218 km (68 km in average) for climate analogues of the Continental transect, from 0 to 715 km (88 km in average) for the ones of the Maritime transect, and from 0 to 428 km (average of 75 km) for the ones of the Eastern Europe transect. In addition to this great spatial proximity – in terms of longitudinal distance – between climate analogues and their reference transect, spatial analysis of the results showed that these three transects of climate shift very rarely overlap with each other (Figure 3). This emphasizes the future north-to-south transect-oriented shift of European cities' climate.

*3.3 Speed of southward velocity*

Table I summarizes the main findings resulting from the southward velocity computation carried out for European cities' climate shift, for the three north-to-south transects and for all the shift time periods (see Appendix Table AII for all detailed results). Overall, the southward velocity of European cities' climate shift greatly differs depending on both their geographical location and the shift time period.

Among the four 30-year shifts, the slowest southward velocity was found for the cities of Jönköping (Sweden) and Cordoba (Spain), with a speed of 0.9 km $year^{-1}$ for the P2-P3 shift.

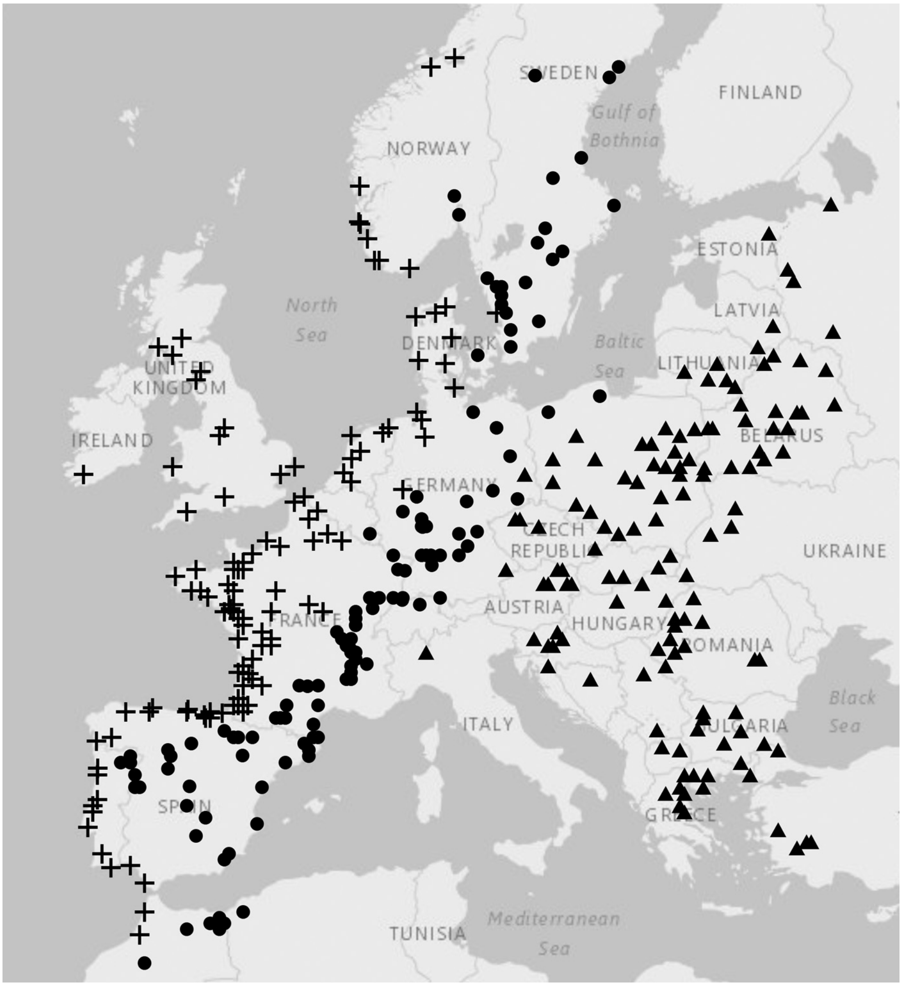



**Figure 3.** Map displaying the investigated cities and their respective climate analogues for the four future 30-year time periods, according to the Maritime (+), Continental (●) and Eastern Europe (▲) transects

Zurich (Switzerland) and Cracow (Poland) exhibited the fastest southward velocity, 34.0 and 38.1 km year$^{-1}$, respectively, for the P4-P5 shift.

Throughout the entire study period P1-P5 (i.e. from 1951-1980 to 2071-2100), Andorra-la-Vella (Andorra) and Berlin (Germany) showed the slowest (2.9 km year$^{-1}$) and quickest (13.2 km year$^{-1}$) climate shift, respectively. Such pace results in considerable displacement of climate in space over the European continent throughout the twenty-first century. As an example, Berlin's climate in 2071-2100 (P5) will be located not less than 1,584 km southwards (South Spain) than its climate in 1951-1980 (P1).

When averaging the southward velocity of cities' climate shift per transects, results showed that the cities of the Maritime transect tend to migrate southwards slower (7.3 km year$^{-1}$ for the P1-P5 shift) than the cities of the two other transects (8.2 and 8.0 km year$^{-1}$). Such conclusion would need to be strengthened by integrating more cities, although it corroborates findings from an earlier study based on rather similar transects (Beniston, 2013).

Results also indicated that the southward velocity of European cities' climate shift is not constant from 1951 to 2100, and instead significantly accelerates throughout the twenty-first century (Table I and Figure 4). It starts from an average of 7.0 km year$^{-1}$ for the P1-P2 shift and almost doubles to reach an average of 13.4 km year$^{-1}$ for the P4-P5 shift. Computations of the averaged southward velocity for the two 60-year shifts also confirmed this finding. It starts from an average of 5.9 km year$^{-1}$ for the P1-P3 shift and almost doubles to reach 11.3 km year$^{-1}$ for the P3-P5 shift. Such doubling of speed is exemplified in Figure 5 for cities of the Continental transect.

A sensitivity analysis has also been performed – using the second best climate analogue of each LOIs rather than their best climate analogues – and showed similar results, in particular for the averaged result over transects and shift time periods (Appendix Table AIII).

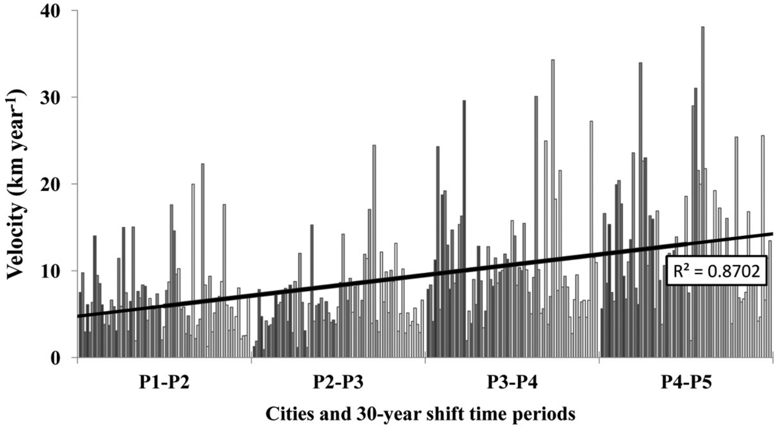
## 4. Discussion

### *4.1 Implications*

Up until now, most of the research on climate analogues and climate shift has aimed to assess the survival and abundance of species as well as the ecological changes of their habitat in response to the shift of climatic conditions. Recent findings (Ash *et al.*, 2016)

**Table I.** Minimum, maximum and mean southward climate shift velocity for the three transects and the seven shift time periods

| Shift time period | Velocity (km year$^{-1}$) | Transects<br>Continental | <br>E. Europe | <br>Maritime | Average (km year$^{-1}$) |
|---|---|---|---|---|---|
| P1-P2 | Min-max | 1.9-15.0 | 2.0-20.0 | 0.8-22.3 | |
| | Mean | 7.3 | 7.8 | 5.9 | 7.0 |
| P2-P3 | Min-max | 0.9-15.3 | 3.9-14.2 | 2.8-24.5 | |
| | Mean | 5.3 | 7.1 | 7.5 | 6.6 |
| P3-P4 | Min-max | 2.0-29.6 | 5.0-30.1 | 2.8-34.3 | |
| | Mean | 11.3 | 11.3 | 10.4 | 11 |
| P4-P5 | Min-max | 5.6-34.0 | 2.0-38.1 | 3.9-25.6 | |
| | Mean | 14.1 | 15.2 | 10.7 | 13.4 |
| P1-P3 | Min-max | 0.9-11.4 | 2.4-11.3 | 2.0-12.1 | |
| | Mean | 5.5 | 6.3 | 5.9 | 5.9 |
| P3-P5 | Min-max | 5.1-19.7 | 5.1-20.2 | 3.9-21.1 | |
| | Mean | 11.9 | 11.9 | 9.9 | 11.3 |
| P1-P5 | Min-max | 3.0-13.2 | 5.4-11.3 | 4.0-10.9 | |
| | Mean | 8.2 | 8.0 | 7.3 | 7.9 |




**Notes:** The linear regression, which depicts the significant rise throughout the twenty-first century, is based on the averaged velocity (over all the investigated cities) for each shift time period

**Figure 4.** Southward velocity of the investigated cities for each 30-year shift time period

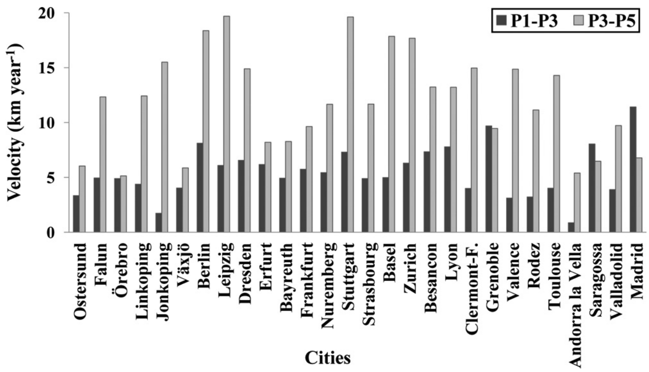



**Figure 5.** Southward velocity of the Continental transect's cities for the two 60-year shift time periods, namely, P1-P3 and P3-P5

highlighted that species either shift their distribution to track climate change or adapt to the changes in their local environmental conditions. Similarly, climate shift in cities will threaten urban dwellers' quality of life and alter cities' functioning because of the new climate-related issues that will appear along the climate shift. Nevertheless, contrary to plants and other animal species, cities' residents are unlikely to shift their distribution to track climate change, and hence will rather have to adapt to these changing conditions.

We have shown that European cities' climate will shift southwards with an average speed of 7.9 km year$^{-1}$ from 1951-1980 to 2071-2100 (P1-P5), under the A1B IPCC SRES scenario. This means that within one human generation (i.e. 25 years), European cities' climate will shift 200 km southwards in average. Such rapid climate shift will undoubtedly have negative implications on the 416 million inhabitants of the 90 investigated cities, and potentially also on many more in similar cases. Moreover, cities' residents will have to not only face the changing climatic conditions but also cope with the acceleration of the rate at which these changes occur, which is expected to double throughout the twenty-first century.

Such finding emphasizes on the strong dynamics of climate change, underlining that climatic conditions will change faster in the near future, without ever reaching an equilibrium state. Hence, an adaptation measure that is efficient at a certain period of time will not necessarily be efficient at another future time period. This brings attention to the fact that both dynamics and acceleration of the rate at which climatic conditions are changing must be taken into account when designing adaptation strategies in urban areas. Although we conducted the analysis over Europe only, findings are likely to be of similar magnitude in other continents.

### *4.2 Potential uses*

In addition of being scientifically based, findings of climate analogues studies are thought to be easily understandable, hence can successfully raise awareness of a lay audience about climate change issues (Kopf *et al.*, 2008; Jylhä *et al.*, 2010; Beniston, 2014; Rohat *et al.*, 2016). Despite being based on a rather complex method, our study is no exception. Its findings, straightforward and readily comprehensible, can potentially raise awareness of urban dwellers and decision-makers about both the magnitude and the pace of climate change, particularly when graphically displayed at city scale (Figure 6). Indeed, when cities' residents and stakeholders visualize on a map that their city's climate is shifting at several

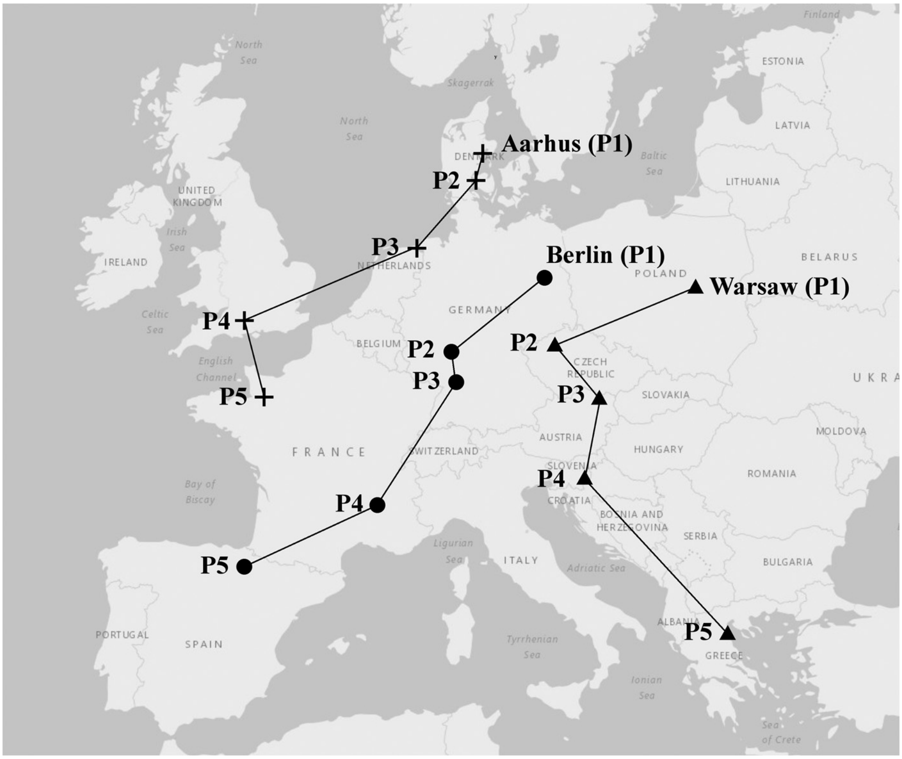



**Figure 6.**
Climate shift over the European continent for the cities of Aarhus (Denmark), Berlin (Germany) and Warsaw (Poland), for the four 30-year shift time periods, namely, P1-P2 (from 1951-1980 to 1981-2010), P2-P3 (from 1981-2010 to 2011-2040), P3-P4 (from 2011-2040 to 2041-2070) and P4-P5 (from 2041-2070 to 2071-2100)

hundred kilometres southwards, they may immediately realize what climate change actually means in terms of the changing climatic conditions and what the magnitude of these changes is. As an example, Figure 6 shows that Berlin's climate is shifting throughout Europe to reach North Spain by the end of the twenty-first century (2071-2100). Knowing that the climate in North Spain is much hotter and drier, with more frequent and intense heat waves, residents of Berlin could easily apprehend the magnitude of climate change and immediately envision the type of future climatic conditions they will have to cope with. Furthermore, displaying the different locations of Berlin's future climate – at different future time periods – might also raise awareness about the pace and dynamics of climate change, emphasizing on the fact that the speed of change is greatly increasing throughout the twenty-first century.

In addition of being a potentially efficient tool to raise awareness and communicate about climate change to a lay audience, the approach described in this paper might also be of great use for decision-makers and urban practitioners in charge of designing and implementing adaptation strategies in urban areas. Indeed, by closely looking at the current climatic conditions of the cities located southwards – along a given transect – decision-makers can readily envision the future climate impacts and vulnerabilities that their respective city will face. In the same line, by looking at the adaptation options that are currently implemented in the cities located southwards, urban practitioners can immediately and easily identify the ones that would have to be implemented in their own city to be well-adapted to the future climatic conditions. Such use of the climate analogues approach as decision-support tool shows great potential (Rohat *et al.*, 2016) but remains poorly explored. Hallegatte *et al.* (2007) showed that climate analogues could help assessing economic impacts of the future climate change and Kellett *et al.* (2011) demonstrated that such approach allows identifying adequate adaptation policies, although some limitations have been recently pointed out (Kellett *et al.*, 2015). One of the added values of our approach lies in the fact that it allows identifying climate analogues for several future time periods. This means that urban practitioners and decision-makers can identify the future climate impacts and efficient adaptation options for different future time periods, by looking at their city's climate analogue for these different periods, such as short-term (2011-2040), medium-term (2041-2070) and long-term (2071-2100) future. To exemplify this point, we computed the return periods of daily maximum temperatures for Aarhus, Berlin and Warsaw and their respective climate analogues for the four future 30-year time periods (Appendix Table AIV). Besides highlighting the great climate proximity between cities and their climate analogues, such results may be of valuable use for identifying future heat-related climate impacts and potential adaptation strategies – through knowledge sharing with climate analogues – for different time horizons of climatic challenges.

Finally, it is worth mentioning that using such approach as a decision-support tool for climate adaptation in urban areas would undeniably strengthen the collaboration among European cities, which is thought to be an important trigger for the implementation of efficient adaptation strategies in urban areas (Reckien *et al.*, 2015). Particularly along a given transect, cities could share experience, adaptation options and best practices. Such transect-oriented network could be embedded within the existing climate-related cities' networks, such as C40-Cities Climate Leadership Group or Covenant of Mayors.

While these potential uses appear promising and beneficial, limitations must be indicated at this point:

- On the one hand, certain limitations are inherent to the climate analogues approach. By taking into account only a limited number of climate statistics (five in this study), such method simplifies the definition of what climate really is. For instance, these five climate parameters do not integrate wind speed and humidity (which both play a role in the perceived temperature) and do not account for the local parameters of urban areas – e.g. the urban heat island – which can largely influence the climate and its impacts. Moreover, climate models' outputs that represent historical climate (1951-1980 and 1981-2010) are subject to spatially uneven biases that may lead to differences with weather stations data.
- On the other hand, certain factors can hinder the exchange of adaptation strategies between cities sharing similar climate at different time periods. For example, two cities of a similar transect might be too different – in terms of size, population's characteristics, functioning, shape, etc. – to efficiently share their adaptation options and best practices, which are often tightly linked to local characteristics. Moreover, the climate-related policies and infrastructures of a city might stem from political choices rather than from climatic conditions (Kellett *et al.*, 2015), hence limiting the utility of sharing adaptation measures between cities. Finally, cities are not always well-adapted to their current climate, meaning that their adaptation strategies should not be taken as an example of good practices. In this case, knowledge sharing would only allow identifying future impacts and vulnerabilities.

## 5. Conclusion

This paper has introduced and described a climate-matching method that can potentially be applied worldwide. As long as reliable climatic projections are available, it allows identifying and ranking climate analogues of any cities. This method also enables assessing the velocity of their climate shift, for any future time periods.

We exemplified this approach for the European continent and applied it on 90 different European cities. We successfully determined (84 per cent of success rate) their climate analogues for four time periods, namely 1981-2010, 2011-2040, 2041-2070 and 2071-2100.

On the basis of the spatial analysis of these climate-matching results, we have shown that European cities' climate will strictly shift southwards in the future. More specifically, this equator-ward climate shift appears to follow particular north-to-south transects, such as the three transects (Maritime, Continental and Eastern Europe) that we predetermined. Using these findings, we computed the southward velocity of this climate shift. Despite the heterogeneity of the results, the averages analysis has highlighted a significant rise (doubling) of the southward climate shift velocity throughout the twenty-first century. It reaches not less than 13.4 km year$^{-1}$ in average for the shift from 2041-2070 to 2071-2100 (P4-P5). This finding is in line with other studies (Burrows *et al.*, 2011; Chen *et al.*, 2011; Diffenbaugh and Field, 2013). Such climate shift and increase of velocity have direct implications for urban inhabitants, who will have to adapt to this rapid climate shift and to the wide range of new climate-related issues that will occur in cities at a constantly growing pace.

One of the major added values of this study is that the findings are both scientifically sound and easily understandable by a lay audience. As a result, these can be used to raise awareness of both stakeholders and urban dwellers about the existence, the magnitude, the pace, and the dynamics of climate change. Knowing that their city's future climate will be similar to the current climate of other cities located southwards and that such shift is expected to double throughout the twenty-first century, people may immediately envision what the future climate will look like in their city and at what pace these changes will occur. Furthermore, we have shown that such approach may also be used as a decision-support tool. It enables cities to learn from each other, in terms of future impacts and vulnerabilities as well as in terms of adaptation options, policies and best practices. Because of the southward climatic shift, knowledge transfer between European cities will be made from southern cities to northern cities, along the same transect. Such practical application of climate analogues might strengthen collaboration between cities and enhance their involvement in climate-related networks. Despite some limitations, mainly associated with the climate matching method and with the differences between cities' characteristics, this exploratory study shows a great potential for future development, particularly regarding its applications as both a communication and decision-support tool in urban areas. On the basis of this exploratory study, further research could integrate different IPCC scenarios (such as the new set of representative concentration pathways) to assess the influence that different radiative forcing has on the southward climate velocity of cities. Further studies could also empirically test the efficiency of such approach as an awareness-raising tool. Finally, on the basis of specific case studies and with the help of cities' stakeholders and policymakers, further research could also demonstrate the applicability of such approach as an efficient decision-support tool for designing and strengthening adaptation strategies in urban areas, at different time horizons.

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## Appendix. Supplementary Material – Equations

Equation for computing the averaged Euclidean distances ($ED_{avg}$) between the LOI's future climate and the current climate of a given grid point, for the five climate variables:

$$ED_{avg} = \sum_{m=1}^{n} abs\left(A_{(m)f}\right) - B_{(m)c}/n$$

where *abs* is the absolute value, $A$ is the LOI's value for the month $m$ for the future time period $f$, and $B$ is the given grid point's value for the month $m$ at the current time period $c$. For monthly mean precipitation and monthly mean temperature variables, number of months $n = 12$; for minimum winter temperature and maximum summer temperature variables, $n = 3$; for annual total precipitation variable, $n = 1$.

Equation for computing the similarity index of climate analogues, based on standardized Euclidean distances (*SED*):

$$SED = \sum_{v=1}^{8} \left[ ED_{avg(v)} - X_S / \sigma_S \right]$$

where $ED_{avg(v)}$ is the averaged Euclidean distance for the climate variable $v$, $Xv$ and $\sigma v$ are, respectively, the mean and the standard deviation of the set of $ED_{avg}$ for all the grid points, for the climate variable $v$.

| Transect | City | Latitude | Longitude | Altitude (m) | Population (inhab.) |
|---|---|---|---|---|---|
| Continental | Östersund | 63.167 | 14.667 | 330 | 45,000 |
| | Falun | 60.6 | 15.616 | 110 | 37,000 |
| | Örebro | 59.26 | 15.22 | 40 | 100,000 |
| | Linköping | 58.4 | 15.61 | 60 | 98,000 |
| | Jönköping | 57.75 | 14.167 | 110 | 85,000 |
| | Växjö | 58.86 | 14.8 | 170 | 56,000 |
| | Berlin | 52.467 | 13.35 | 40 | 3,500,000 |
| | Leipzig | 51.333 | 12.417 | 110 | 523,000 |
| | Dresden | 51.05 | 13.73 | 120 | 524,000 |
| | Erfurt | 50.97 | 11.03 | 190 | 206,000 |
| | Bayreuth | 49.95 | 11.58 | 340 | 73,000 |
| | Frankfurt | 50.1 | 8.683 | 100 | 681,000 |
| | Nuremberg | 49.45 | 11.083 | 320 | 506,000 |
| | Stuttgart | 48.776 | 9.17 | 250 | 607,000 |
| | Strasbourg | 48.583 | 7.75 | 140 | 272,000 |
| | Basel | 47.55 | 7.6 | 260 | 165,000 |
| | Zurich | 47.378 | 8.54 | 410 | 379,000 |
| | Besancon | 47.24 | 6.03 | 250 | 117,000 |
| | Geneva | 46.217 | 6.15 | 370 | 189,000 |
| | Lyon | 45.767 | 4.833 | 170 | 485,000 |
| | Clermont-Ferrand | 45.78 | 3.08 | 410 | 140,000 |
| | Grenoble | 45.187 | 5.72 | 220 | 156,000 |
| | Valence | 44.93 | 4.89 | 130 | 62,000 |
| | Rodez | 44.35 | 2.567 | 630 | 25,000 |
| | Toulouse | 43.617 | 1.45 | 140 | 442,000 |
| | Andorra la Vella | 42.51 | 1.523 | 990 | 23,000 |
| | Saragossa | 41.65 | −0.9 | 210 | 666,000 |
| | Valladolid | 41.63 | −4.72 | 700 | 307,000 |
| | Madrid | 40.417 | −3.717 | 650 | 3,165,000 |
| | Cordoba | 37.883 | −4.767 | 130 | 329,000 |
| Eastern Europe | St. Petersburg | 59.917 | 30.417 | 20 | 5,222,000 |
| | Pskov | 57.8 | 28.433 | 50 | 205,000 |
| | Velikiye Luki | 56.33 | 30.533 | 100 | 99,000 |
| | Rēzekne | 56.5 | 27.34 | 160 | 33,000 |
| | Daugavpils | 55.875 | 26.53 | 110 | 90,000 |
| | Polotsk | 55.483 | 28.8 | 130 | 83,000 |
| | Vitebsk | 55.183 | 30.167 | 160 | 348,000 |
| | Kaunas | 54.89 | 23.89 | 30 | 309,000 |
| | Vilnius | 54.667 | 25.317 | 100 | 536,000 |
| | Minsk | 53.92 | 27.49 | 210 | 1,894,000 |
| | Bialystok | 53.34 | 23.166 | 130 | 295,000 |
| | Pinsk | 52.12 | 26.1 | 140 | 135,000 |
| | Brest-Litovsk | 52.08 | 23.7 | 170 | 323,700 |
| | Warsaw | 52.217 | 21.005 | 110 | 1,715,000 |
| | Lodz | 51.783 | 19.467 | 210 | 722,000 |
| | Lublin | 51.248 | 22.57 | 190 | 348,000 |
| | Lutsk | 50.75 | 25.335 | 190 | 212,000 |
| | Cracow | 50.067 | 19.933 | 220 | 759,000 |
| | Lviv | 49.85 | 24.02 | 290 | 724,000 |
| | Kosice | 48.716 | 21.25 | 200 | 241,000 |
| | Budapest | 47.498 | 19.04 | 110 | 1,732,000 |
| | Debrecen | 47.529 | 21.639 | 120 | 205,000 |

(*continued*)

**Table AI.**
List of the 90 investigated cities, with their coordinates, altitude and population

| Transect | City | Latitude | Longitude | Altitude (m) | Population (inhab.) |
|---|---|---|---|---|---|
| | Mukacheve | 48.45 | 22.75 | 120 | 86,000 |
| | Cluj-Napoca | 46.76 | 23.583 | 340 | 304,000 |
| | Timisoara | 45.76 | 21.23 | 90 | 307,000 |
| | Belgrade | 44.817 | 20.467 | 170 | 1,352,000 |
| | Prishtina | 42.66 | 21.166 | 650 | 146,000 |
| | Sofia | 42.7 | 23.33 | 550 | 1,212,000 |
| | Plovdiv | 42.146 | 24.75 | 170 | 339,000 |
| | Skopje | 41.997 | 21.433 | 250 | 537,000 |
| Maritime | Trondheim | 63.6 | 10.383 | 10 | 179,000 |
| | Bergen | 60.383 | 5.333 | 10 | 266,000 |
| | Haugesund | 59.43 | 5.28 | 15 | 37,000 |
| | Stavanger | 58.967 | 5.75 | 10 | 129,000 |
| | Kristiansand | 58.15 | 8 | 10 | 88,000 |
| | Aalborg | 57.05 | 9.919 | 10 | 204,000 |
| | Aarhus | 56.15 | 10.22 | 20 | 320,000 |
| | Herning | 56.762 | 8.317 | 50 | 87,000 |
| | Esbjerg | 55.467 | 8.467 | 20 | 116,000 |
| | Bremen | 53.083 | 8.8 | 10 | 547,000 |
| | Groningen | 53.218 | 6.56 | 10 | 190,000 |
| | Amsterdam | 52.38 | 4.9 | 10 | 780,000 |
| | Rotterdam | 51.917 | 4.483 | 10 | 611,000 |
| | Calais | 50.95 | 1.85 | 10 | 73,000 |
| | Lille | 50.65 | 3.083 | 20 | 228,000 |
| | Rouen | 49.433 | 1.083 | 20 | 111,000 |
| | Caen | 49.18 | −0.37 | 20 | 109,000 |
| | Rennes | 48.1 | −1.667 | 40 | 208,000 |
| | Brest | 48.39 | −4.48 | 50 | 140,000 |
| | Vannes | 47.65 | −2.76 | 30 | 54,000 |
| | Nantes | 47.233 | −1.538 | 10 | 293,000 |
| | Bordeaux | 44.833 | −0.567 | 10 | 244,000 |
| | San-Sebastián | 43.32 | −1.98 | 10 | 187,000 |
| | Bilbao | 43.25 | −2.933 | 20 | 347,000 |
| | Santander | 43.46 | −3.805 | 10 | 176,000 |
| | Gijón | 43.53 | −5.7 | 20 | 276,000 |
| | Vigo | 42.23 | −8.67 | 10 | 295,000 |
| | Porto | 41.15 | −8.617 | 50 | 231,000 |
| | Lisbon | 38.733 | −9.133 | 50 | 531,000 |
| | Faro | 37.03 | −7.91 | 20 | 65,000 |

**Source:** http://ec.europa.eu/eurostat/statistics-explained/index.php/Statistics_on_European_cities

**Table AI.**

**Table AII.**
Full results of the southward velocity computations for the 90 investigated cities and the seven shift time periods

| Cities of each transect | 1950-1980 to 1980-2010 Distance (km) | 1950-1980 to 1980-2010 Velocity (km/year) | 1980-2010 to 2010-2040 Distance | 1980-2010 to 2010-2040 Velocity | 2010-2040 to 2040-2070 Distance | 2010-2040 to 2040-2070 Velocity | 2040-2070 to 2070-2100 Distance | 2040-2070 to 2070-2100 Velocity | 1950-1980 to 2010-2040 Distance | 1950-1980 to 2010-2040 Velocity | 2010-2040 to 2070-2100 Distance | 2010-2040 to 2070-2100 Velocity | 1950-1980 to 2070-2100 Distance | 1950-1980 to 2070-2100 Velocity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Continental* | | | | | | | | | | | | | | |
| Östersund | 225.00 | 7.50 | 38.00 | 1.27 | 236.00 | 7.87 | 169.00 | 5.63 | 200.00 | 3.33 | 362.00 | 6.03 | 430.00 | 3.58 |
| Falun | 293.00 | 9.77 | 57.00 | 1.90 | 251.00 | 8.37 | 498.00 | 16.60 | 297.00 | 4.95 | 740.00 | 12.33 | 711.00 | 5.93 |
| Örebro | 89.00 | 2.97 | 235.00 | 7.83 | 125.00 | 4.17 | 257.00 | 8.57 | 294.00 | 4.90 | 308.00 | 5.13 | 600.00 | 5.00 |
| Linköping | 183.00 | 6.10 | 142.00 | 4.73 | 337.00 | 11.23 | 460.00 | 15.33 | 263.00 | 4.38 | 745.00 | 12.42 | 1007.00 | 8.39 |
| Jönköping | 88.00 | 2.93 | 28.00 | 0.93 | 729.00 | 24.30 | 225.00 | 7.50 | 104.00 | 1.73 | 930.00 | 15.50 | 1031.00 | 8.59 |
| Växjö | 191.00 | 6.37 | 127.00 | 4.23 | 167.00 | 5.57 | 195.00 | 6.50 | 242.00 | 4.03 | 352.00 | 5.87 | 594.00 | 4.95 |
| Berlin | 420.00 | 14.00 | 109.00 | 3.63 | 562.00 | 18.73 | 598.00 | 19.93 | 487.00 | 8.12 | 1102.00 | 18.37 | 1579.00 | 13.16 |
| Leipzig | 284.00 | 9.47 | 113.00 | 3.77 | 576.00 | 19.20 | 612.00 | 20.40 | 365.00 | 6.08 | 1181.00 | 19.68 | 1543.00 | 12.86 |
| Dresden | 256.00 | 8.53 | 137.00 | 4.57 | 389.00 | 12.97 | 531.00 | 17.70 | 393.00 | 6.55 | 893.00 | 14.88 | 1269.00 | 10.58 |
| Erfurt | 182.00 | 6.07 | 215.00 | 7.17 | 237.00 | 7.90 | 281.00 | 9.37 | 370.00 | 6.17 | 492.00 | 8.20 | 852.00 | 7.10 |
| Bayreuth | 115.00 | 3.83 | 183.00 | 6.10 | 441.00 | 14.70 | 203.00 | 6.77 | 296.00 | 4.93 | 496.00 | 8.27 | 779.00 | 6.49 |
| Frankfurt | 156.00 | 5.20 | 191.00 | 6.37 | 257.00 | 8.57 | 331.00 | 11.03 | 344.00 | 5.73 | 578.00 | 9.63 | 918.00 | 7.65 |
| Nuremberg | 112.00 | 3.73 | 223.00 | 7.43 | 293.00 | 9.77 | 408.00 | 13.60 | 326.00 | 5.43 | 699.00 | 11.65 | 1025.00 | 8.54 |
| Stuttgart | 199.00 | 6.63 | 239.00 | 7.97 | 460.00 | 15.33 | 708.00 | 23.60 | 438.00 | 7.30 | 1177.00 | 19.62 | 1536.00 | 12.80 |
| Strasbourg | 176.00 | 5.87 | 125.00 | 4.17 | 489.00 | 16.30 | 240.00 | 8.00 | 294.00 | 4.90 | 700.00 | 11.67 | 991.00 | 8.26 |
| Basel | 93.00 | 3.10 | 250.00 | 8.33 | 888.00 | 29.60 | 184.00 | 6.13 | 299.00 | 4.98 | 1071.00 | 17.85 | 1354.00 | 11.28 |
| Zurich | 343.00 | 11.43 | 86.00 | 2.87 | 59.00 | 1.97 | 1019.00 | 33.97 | 378.00 | 6.30 | 1060.00 | 17.67 | 1425.00 | 11.88 |
| Besancon | 177.00 | 5.90 | 263.00 | 8.77 | 161.00 | 5.37 | 679.00 | 22.63 | 440.00 | 7.33 | 794.00 | 13.23 | 1200.00 | 10.00 |
| Geneva | | | | | | | | | | | | | | |
| Lyon | 450.00 | 15.00 | 35.00 | 1.17 | 118.00 | 3.93 | 690.00 | 23.00 | 467.00 | 7.78 | 793.00 | 13.22 | 1063.00 | 8.86 |
| Clermont-Ferrand | | | | | 383.00 | 12.77 | 516.00 | 17.20 | 240.00 | 4.00 | 898.00 | 14.97 | 975.00 | 8.13 |
| Grenoble | 224.00 | 7.47 | 360.00 | 12.00 | 270.00 | 9.00 | 318.00 | 10.60 | 581.00 | 9.68 | 568.00 | 9.47 | 1141.00 | 9.51 |
| Valence | | | | | 635.00 | 21.17 | 368.00 | 12.27 | 187.00 | 3.12 | 891.00 | 14.85 | 946.00 | 7.88 |
| Rodez | 92.00 | 3.07 | 191.00 | 6.37 | 184.00 | 6.13 | 490.00 | 16.33 | 193.00 | 3.22 | 668.00 | 11.13 | 839.00 | 6.99 |
| Toulouse | 194.00 | 6.47 | 93.00 | 3.10 | 385.00 | 12.83 | 478.00 | 15.93 | 241.00 | 4.02 | 857.00 | 14.28 | 1018.00 | 8.48 |
| Andorra la Vella | | | | | | | | | 52.00 | 0.87 | 324.00 | 5.40 | 354.00 | 2.95 |
| Saragossa | 451.00 | 15.03 | 35.00 | 1.17 | 265.00 | 8.83 | 169.00 | 5.63 | 482.00 | 8.03 | 388.00 | 6.47 | 794.00 | 6.62 |
| Valladolid | 58.00 | 1.93 | 187.00 | 6.23 | 103.00 | 3.43 | 507.00 | 16.90 | 234.00 | 3.90 | 583.00 | 9.72 | 816.00 | 6.80 |
| Madrid | 229.00 | 7.63 | 458.00 | 15.27 | 161.00 | 5.37 | 267.00 | 8.90 | 685.00 | 11.42 | 407.00 | 6.78 | 864.00 | 7.20 |
| Cordoba | 390.00 | 13.00 | 28.00 | 0.93 | | | | | 418.00 | 6.97 | | | | |

(*continued*)

Table AII.

| Cities of each transect | 1950-1980 to 1980-2010 Distance (km) | 1950-1980 to 1980-2010 Velocity (km/year) | 1980-2010 to 2010-2040 Distance | 1980-2010 to 2010-2040 Velocity | 2010-2040 to 2040-2070 Distance | 2010-2040 to 2040-2070 Velocity | 2040-2070 to 2070-2100 Distance | 2040-2070 to 2070-2100 Velocity | 1950-1980 to 2010-2040 Distance | 1950-1980 to 2010-2040 Velocity | 2010-2040 to 2070-2100 Distance | 2010-2040 to 2070-2100 Velocity | 1950-1980 to 2070-2100 Distance | 1950-1980 to 2070-2100 Velocity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Eastern Europe* | | | | | | | | | | | | | | |
| St. Petersburg | 206.00 | 6.87 | 126.00 | 4.20 | 383.00 | 12.77 | 115.00 | 3.83 | 239.00 | 3.98 | 475.00 | 7.92 | 708.00 | 5.90 |
| Pskov | 251.00 | 8.37 | 180.00 | 6.00 | 270.00 | 9.00 | 318.00 | 10.60 | 393.00 | 6.55 | 559.00 | 9.32 | 896.00 | 7.47 |
| Velikiye Luki | 246.00 | 8.20 | 185.00 | 6.17 | 246.00 | 8.20 | 349.00 | 11.63 | 363.00 | 6.05 | 577.00 | 9.62 | 859.00 | 7.16 |
| Rēzekne | 129.00 | 4.30 | 206.00 | 6.87 | 344.00 | 11.47 | 360.00 | 12.00 | 333.00 | 5.55 | 701.00 | 11.68 | 886.00 | 7.38 |
| Daugavpils | 204.00 | 6.80 | 129.00 | 4.30 | 257.00 | 8.57 | 353.00 | 11.77 | 319.00 | 5.32 | 609.00 | 10.15 | 859.00 | 7.16 |
| Polotsk | 179.00 | 5.97 | 193.00 | 6.43 | 295.00 | 9.83 | 370.00 | 12.33 | 349.00 | 5.82 | 661.00 | 11.02 | 922.00 | 7.68 |
| Vitebsk | 168.00 | 5.60 | 154.00 | 5.13 | 302.00 | 10.07 | 417.00 | 13.90 | 322.00 | 5.37 | 717.00 | 11.95 | 975.00 | 8.13 |
| Kaunas | 220.00 | 7.33 | 122.00 | 4.07 | 358.00 | 11.93 | 325.00 | 10.83 | 342.00 | 5.70 | 630.00 | 10.50 | 956.00 | 7.97 |
| Vilnius | 172.00 | 5.73 | 130.00 | 4.33 | 340.00 | 11.33 | 263.00 | 8.77 | 302.00 | 5.03 | 601.00 | 10.02 | 808.00 | 6.73 |
| Minsk | 61.00 | 2.03 | 116.00 | 3.87 | 313.00 | 10.43 | 342.00 | 11.40 | 177.00 | 2.95 | 644.00 | 10.73 | 754.00 | 6.28 |
| Bialystok | 106.00 | 3.53 | 175.00 | 5.83 | 473.00 | 15.77 | 557.00 | 18.57 | 275.00 | 4.58 | 802.00 | 13.37 | 1074.00 | 8.95 |
| Pinsk | 232.00 | 7.73 | 260.00 | 8.67 | 420.00 | 14.00 | 223.00 | 7.43 | 448.00 | 7.47 | 546.00 | 9.10 | 986.00 | 8.22 |
| Brest-Litovsk | 261.00 | 8.70 | 427.00 | 14.23 | 250.00 | 8.33 | 59.00 | 1.97 | 676.00 | 11.27 | 306.00 | 5.10 | 908.00 | 7.57 |
| Warsaw | 528.00 | 17.60 | 254.00 | 8.47 | 311.00 | 10.37 | 870.00 | 29.00 | 538.00 | 8.97 | 1076.00 | 17.93 | 1350.00 | 11.25 |
| Lodz | 438.00 | 14.60 | 198.00 | 6.60 | 300.00 | 10.00 | 931.00 | 31.03 | 573.00 | 9.55 | 1209.00 | 20.15 | 1318.00 | 10.98 |
| Lublin | 288.00 | 9.60 | 274.00 | 9.13 | 464.00 | 15.47 | 647.00 | 21.57 | 562.00 | 9.37 | 1086.00 | 18.10 | 1236.00 | 10.30 |
| Lutsk | 307.00 | 10.23 | 157.00 | 5.23 | 303.00 | 10.10 | 599.00 | 19.97 | 463.00 | 7.72 | 899.00 | 14.98 | 1002.00 | 8.35 |
| Cracow | 167.00 | 5.57 | 245.00 | 8.17 | 226.00 | 7.53 | 1143.00 | 38.10 | 412.00 | 6.87 | 1203.00 | 20.05 | 1087.00 | 9.06 |
| Lviv | 175.00 | 5.83 | 253.00 | 8.43 | 151.00 | 5.03 | 653.00 | 21.77 | 427.00 | 7.12 | 801.00 | 13.35 | 1226.00 | 10.22 |
| Kosice | | | | | 296.00 | 9.87 | 424.00 | 14.13 | 144.00 | 2.40 | 670.00 | 11.17 | 648.00 | 5.40 |
| Budapest | | | | | 474.00 | 15.80 | 197.00 | 6.57 | 265.00 | 4.42 | 654.00 | 10.90 | 872.00 | 7.27 |
| Debrecen | 82.00 | 2.73 | 139.00 | 4.63 | 277.00 | 9.23 | 346.00 | 11.53 | 215.00 | 3.58 | 619.00 | 10.32 | 821.00 | 6.84 |
| Mukacheve | 144.00 | 4.80 | 198.00 | 6.60 | 902.00 | 30.07 | 267.00 | 8.90 | 309.00 | 5.15 | 705.00 | 11.75 | 1265.00 | 10.54 |
| Cluj-Napoca | 281.00 | 9.37 | 316.00 | 10.53 | 369.00 | 12.30 | | | 487.00 | 8.12 | | | | |
| Timisoara | 77.00 | 2.57 | 357.00 | 11.90 | 304.00 | 10.13 | 407.00 | 13.57 | 423.00 | 7.05 | 560.00 | 9.33 | 952.00 | 7.93 |
| Belgrade | 599.00 | 19.97 | 342.00 | 11.40 | 153.00 | 5.10 | 577.00 | 19.23 | 488.00 | 8.13 | 579.00 | 9.65 | 1029.00 | 8.58 |
| Prishtina | | | | | | | | | | | | | 842.00 | 7.02 |
| Sofia | | | | | | | | | | | | | | |
| Plovdiv | 303.00 | 10.10 | | | | | | | | | | | | |
| Skopje | | | | | | | 706.00 | 23.53 | | | | | 802.00 | 6.68 |

*(continued)*

Table AII.

| Cities of each transect | 1950-1980 to 1980-2010 Distance (km) | 1950-1980 to 1980-2010 Velocity (km/year) | 1980-2010 to 2010-2040 Distance | 1980-2010 to 2010-2040 Velocity | 2010-2040 to 2040-2070 Distance | 2010-2040 to 2040-2070 Velocity | 2040-2070 to 2070-2100 Distance | 2040-2070 to 2070-2100 Velocity | 1950-1980 to 2010-2040 Distance | 1950-1980 to 2010-2040 Velocity | 2010-2040 to 2070-2100 Distance | 2010-2040 to 2070-2100 Velocity | 1950-1980 to 2070-2100 Distance | 1950-1980 to 2070-2100 Velocity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Maritime* | | | | | | | | | | | | | | |
| Trondheim | 66.00 | 2.20 | 512.00 | 17.07 | 169.00 | 5.63 | 346.00 | 11.53 | 473.00 | 7.88 | 502.00 | 8.37 | 963.00 | 8.03 |
| Bergen | 112.00 | 3.73 | 119.00 | 3.97 | 749.00 | 24.97 | 517.00 | 17.23 | 228.00 | 3.80 | 1221.00 | 20.35 | 1311.00 | 10.93 |
| Haugesund | 133.00 | 4.43 | 734.00 | 24.47 | 115.00 | 3.83 | 317.00 | 10.57 | 728.00 | 12.13 | 390.00 | 6.50 | 1021.00 | 8.51 |
| Stavanger | 670.00 | 22.33 | 128.00 | 4.27 | 211.00 | 7.03 | 335.00 | 11.17 | 687.00 | 11.45 | 503.00 | 8.38 | 1114.00 | 9.28 |
| Kristiansand | 251.00 | 8.37 | 89.00 | 2.97 | 1029.00 | 34.30 | 481.00 | 16.03 | 311.00 | 5.18 | 1268.00 | 21.13 | 1186.00 | 9.88 |
| Aalborg | 38.00 | 1.27 | 365.00 | 12.17 | 548.00 | 18.27 | 320.00 | 10.67 | 390.00 | 6.50 | 866.00 | 14.43 | 1184.00 | 9.87 |
| Aarhus | 89.00 | 2.97 | 296.00 | 9.87 | 647.00 | 21.57 | 287.00 | 9.57 | 376.00 | 6.27 | 758.00 | 12.63 | 1125.00 | 9.38 |
| Herning | 281.00 | 9.37 | 192.00 | 6.40 | 232.00 | 7.73 | 117.00 | 3.90 | 461.00 | 7.68 | 281.00 | 4.68 | 738.00 | 6.15 |
| Esbjerg | 154.00 | 5.13 | 155.00 | 5.17 | 244.00 | 8.13 | 762.00 | 25.40 | 177.00 | 2.95 | 1005.00 | 16.75 | 1111.00 | 9.26 |
| Bremen | 206.00 | 6.87 | 302.00 | 10.07 | 281.00 | 9.37 | 207.00 | 6.90 | 493.00 | 8.22 | 480.00 | 8.00 | 972.00 | 8.10 |
| Groningen | 211.00 | 7.03 | 264.00 | 8.80 | 244.00 | 8.13 | 192.00 | 6.40 | 475.00 | 7.92 | 435.00 | 7.25 | 906.00 | 7.55 |
| Amsterdam | 263.00 | 8.77 | 395.00 | 13.17 | 140.00 | 4.67 | 203.00 | 6.77 | 596.00 | 9.93 | 336.00 | 5.60 | 851.00 | 7.09 |
| Rotterdam | 529.00 | 17.63 | 91.00 | 3.03 | 83.00 | 2.77 | 226.00 | 7.53 | 615.00 | 10.25 | 308.00 | 5.13 | 852.00 | 7.10 |
| Calais | 181.00 | 6.03 | 152.00 | 5.07 | 200.00 | 6.67 | 504.00 | 16.80 | 327.00 | 5.45 | 584.00 | 9.73 | 895.00 | 7.46 |
| Lille | 94.00 | 3.13 | 306.00 | 10.20 | 286.00 | 9.53 | 289.00 | 9.63 | 393.00 | 6.55 | 534.00 | 8.90 | 863.00 | 7.19 |
| Rouen | 174.00 | 5.80 | 85.00 | 2.83 | 139.00 | 4.63 | 269.00 | 8.97 | 259.00 | 4.32 | 401.00 | 6.68 | 659.00 | 5.49 |
| Caen | 96.00 | 3.20 | 154.00 | 5.13 | 192.00 | 6.40 | 306.00 | 10.20 | 250.00 | 4.17 | 471.00 | 7.85 | 593.00 | 4.94 |
| Rennes | 142.00 | 4.73 | 111.00 | 3.70 | 198.00 | 6.60 | 126.00 | 4.20 | 235.00 | 3.92 | 321.00 | 5.35 | 499.00 | 4.16 |
| Brest | 241.00 | 8.03 | 125.00 | 4.17 | 139.00 | 4.63 | 140.00 | 4.67 | 358.00 | 5.97 | 279.00 | 4.65 | 582.00 | 4.85 |
| Vannes | 91.00 | 3.03 | 338.00 | 11.27 | 180.00 | 6.00 | | | 393.00 | 6.55 | | | | |
| Nantes | 64.00 | 2.13 | 171.00 | 5.70 | 198.00 | 6.60 | 767.00 | 25.57 | 225.00 | 3.75 | 911.00 | 15.18 | 997.00 | 8.31 |
| Bordeaux | 75.00 | 2.50 | 115.00 | 3.83 | 817.00 | 27.23 | 199.00 | 6.63 | 136.00 | 2.27 | 919.00 | 15.32 | 1033.00 | 8.61 |
| San-Sebastián | 76.00 | 2.53 | 86.00 | 2.87 | 345.00 | 11.50 | 344.00 | 11.47 | 154.00 | 2.57 | 610.00 | 10.17 | 724.00 | 6.03 |
| Bilbao | | | | | | | | | | | | | 623.00 | 5.19 |
| Santander | | | | | | | | | | | | | 565.00 | 4.71 |
| Gijón | 23.00 | 0.77 | 101.00 | 3.37 | | | | | 117.00 | 1.95 | | | | |
| Vigo | | | | | | | | | 151.00 | 2.52 | | | | |
| Porto | 171.00 | 5.70 | | | | | | | | | | | | |
| Lisbon | | | | | 107.00 | 3.57 | 139.00 | 4.63 | 207.00 | 3.45 | 232.00 | 3.87 | 482.00 | 4.02 |
| Faro | | | | | | | | | 351.00 | 5.85 | | | | |

(*continued*)

| Cities of each transect | 1950-1980 to 1980-2010 | | 1980-2010 to 2010-2040 | | 2010-2040 to 2040-2070 | | 2040-2070 to 2070-2100 | | 1950-1980 to 2010-2040 | | 2010-2040 to 2070-2100 | | 1950-1980 to 2070-2100 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Distance (km) | Velocity (km/year) | Distance | Velocity | Distance | Velocity | Distance | Velocity | Distance | Velocity | Distance | Velocity | Distance | Velocity |
| Average Continental | 218.08 | 7.27 | 159.54 | 5.32 | 339.30 | 11.31 | 422.26 | 14.08 | 331.38 | 5.52 | 716.32 | 11.94 | 987.64 | 8.23 |
| Average Eastern Europe | 232.96 | 7.77 | 214.00 | 7.13 | 337.73 | 11.26 | 454.54 | 15.15 | 378.62 | 6.31 | 715.56 | 11.93 | 964.48 | 8.04 |
| Average Maritime | 177.24 | 5.91 | 224.42 | 7.48 | 312.21 | 10.41 | 321.43 | 10.71 | 354.30 | 5.90 | 591.96 | 9.87 | 873.96 | 7.28 |
| Average all transects | 209.54 | 6.98 | 198.24 | 6.61 | 330.32 | 11.01 | 402.79 | 13.43 | 353.90 | 5.90 | 678.43 | 11.31 | 944.30 | 7.87 |

**Note:** Blank cells represent combinations of cities and shift time periods for which no climate analogue was found

**Table AII.**

**Table AIII.** Sensitivity analysis showing the absolute difference of minimum, maximum and mean southward climate shift velocity (for the three transects and the seven shift time periods) when computations are based on the second best climate analogues (for each LOIs) rather than on the best climate analogues

| Shift time period | Velocity (km year$^{-1}$) | Transects Continental | E. Europe | Maritime | Average (km year$^{-1}$) |
|---|---|---|---|---|---|
| P1-P2 | Min-max | 1.5-0.5 | 1.2-1.4 | 0.4-0.7 | |
| | Mean | 0.2 | 0.3 | 0.1 | 0.2 |
| P2-P3 | Min-max | 1.1-3.2 | 0.5-2.1 | 2.0-1.3 | |
| | Mean | 0.2 | 0.3 | 0.4 | 0.4 |
| P3-P4 | Min-max | 0.9-0.8 | 1.9-3.1 | 0.8-2.4 | |
| | Mean | 0.2 | 0.4 | 0.2 | 0.3 |
| P4-P5 | Min-max | 0.3-1.8 | 1.1-2.4 | 0.1-2.8 | |
| | Mean | 0.3 | 0.3 | 0.2 | 0.3 |
| P1-P3 | Min-max | 0.7-2.5 | 0.5-3.1 | 1.5-1.7 | |
| | Mean | 0.2 | 0.1 | 0.1 | 0.1 |
| P3-P5 | Min-max | 0.6-4.7 | 0.8-3.3 | 1.2-3.7 | |
| | Mean | 0.1 | 0.4 | 0.4 | 0.4 |
| P1-P5 | Min-max | 1.1-4.2 | 0.8-3.8 | 1.4-2.5 | |
| | Mean | 0.2 | 0.3 | 0.3 | 0.3 |

**Table AIV.** Return periods in years of mean daily maximum temperatures for Aarhus (Denmark), Berlin (Germany) and Warsaw (Poland) and their respective climate analogues for the four future 30-year time periods

| Cities | Daily max temperature (°C) | P1 city | P2 city | P2 climate analogue | P3 city | P3 climate analogue | P4 city | P4 climate analogue | P5 city | P5 climate analogue |
|---|---|---|---|---|---|---|---|---|---|---|
| Aarhus | 29 | 23 | 11 | 11 | 9 | 9 | 5 | 3 | 2 | 2 |
| | 31 | 78 | 33 | 30 | 26 | 22 | 13 | 8 | 4 | 4 |
| | 33 | 261 | 98 | 85 | 79 | 60 | 34 | 25 | 9 | 9 |
| | 35 | 884 | 290 | 239 | 240 | 161 | 86 | 74 | 21 | 23 |
| Berlin | 35 | 18 | 13 | 19 | 7 | 7 | 5 | 6 | 1 | 1.0 |
| | 37 | 48 | 40 | 52 | 17 | 18 | 13 | 14 | 4 | 4 |
| | 39 | 134 | 119 | 148 | 40 | 43 | 33 | 39 | 6 | 9 |
| | 41 | 377 | 359 | 419 | 99 | 106 | 85 | 108 | 12 | 17 |
| Warsaw | 33 | 10 | 6 | 7 | 4 | 4 | 3 | 3 | 2 | 2 |
| | 35 | 43 | 19 | 23 | 9 | 8 | 7 | 7 | 3 | 4 |
| | 37 | 180 | 65 | 77 | 23 | 20 | 22 | 20 | 9 | 10 |
| | 39 | 767 | 223 | 261 | 73 | 62 | 62 | 51 | 23 | 29 |