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Key Points:
- Most meteorological stations in Europe are in rural surroundings
- The contribution of the urbanization on the warming of Europe is small
- The urbanization-related warming has strong seasonality

Supporting Information:
- Table S3
- Table S2
- Table S1
- Text S1
- Readme

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The effects of urbanization on the rise of the European temperature since 1960

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Abstract The effects of urbanization on the rise of the European daily mean temperature is quantified by comparing European-averaged temperatures based on all meteorological stations in the European Climate Assessment and Dataset with those based on three subsets of stations: from rural areas, from areas with low growth in urbanization, and from areas characterized by relatively low-temperature increase. Land cover information is obtained using the CORINE (Coordination of Information on the Environment) data set, showing that most stations (75%) have a small percentage (up to 10%) of urban area within a 10 km radius and 81% saw no more than 1% change in urbanization between 1990 and 2006. The results show that urbanization explains 0.0026°C/decade of the annual-averaged pan-European temperature trend of 0.179°C/decade. This trend has a strong seasonality, being the largest in summer. Averaged over time, the effects of urbanization on the European-averaged temperature has a strong seasonality as well.

1. Introduction

The Urban Heat Island (UHI) effect is the phenomenon where cities are experiencing higher temperatures than the surrounding rural areas. The air in the urban canopy layer is warmer than the air over the nonurban surrounding areas due to the human modification of the surface, where several possible physical explanations exist for the change in surface energy and radiation balance [*Oke*, 1982].

Santamouris [2007] summarized the UHI research on European cities from the past 15 years using ground-based stations and found large regional differences in UHI amplitude. Using satellite data, *Zhou et al.* [2013] compared temperature in clusters of cities in Europe with that of their surroundings and found that the radiant surface temperature difference is seasonally depended, with summer having the highest temperature difference in most parts of Europe, and temperature contrasts between cities and their surroundings are larger in spring than in autumn.

These studies point to the question as to what extent the warming trend in the air temperature *averaged* over Europe is affected by local effects like the UHI in terms of amplitude and seasonality. This is addressed by quantifying the contribution of urbanization, i.e., changes in the UHI, in the warming of Europe. Earlier, *van der Schrier et al.* [2013] used a global seasonally independent estimate of 0.005°C per decade for their urbanization-related temperature trend for Europe [*Brohan et al.*, 2006]. The current study aims to critically assess the amplitude and the lack of seasonality of this estimate for the European situation.

An estimate of the urbanization-related warming of Europe is obtained by selecting subsets of stations unaffected by the UHI and calculating a European-averaged temperature using these subsets. Stations are classified in three different ways: (1) using the urbanization at the 2006 level around a station to identify stations in rural areas, (2) using the growth of the urbanization in the immediate vicinity of the station in the 1990–2006 period, and (3) by the temperature trend of the station. The three sets give a small ensemble of the urbanization-related trend and an uncertainty estimate.

Recently, *Stewart and Oke* [2012] introduced a new research framework for UHI studies motivated by inadequacies of a simple urban-rural division. However, such detailed metadata of the meteorological stations is currently missing for all European stations and we need to revert to simpler methods of distinction.

2. Data Sets

2.1. Land Cover Data Set

CORINE (Coordination of Information on the Environment) is established by the European Union in 1985 and is a land cover inventory using 44 land cover classes based on satellite images at 100×100 m^2 resolution. There are three CORINE European land cover inventories, the first one was issued in 1990 (CLC90), with updates in 2000 (CLC2000) and 2006 (CLC2006). The number of participating countries has changed over the years (see the supporting information). Although the detail of land cover information and the use of 44 land cover classes are kept constant throughout the project, mistakes in classification have been corrected and unclear definitions of nomenclature elements have improved over the years [*European Environment Agency (EEA)*, 2012].

The drawback of the exclusive use of CORINE in providing land use information is that uncertainty in the land use description, which can be obtained by comparing with other sources, is ignored.

A selection has been made of classes that characterize an urban area. The group of the artificial surfaces has 11 land cover classes, six of those were used to define an urban area: the continuous urban fabric, the discontinuous urban fabric, the industrial or commercial units, and the road and rail networks and associated land, port areas, and airports. Classes that characterize an urban area represent the type of land that is mostly covered by structures, transport networks, and buildings including artificially surfaced areas which cover at least 80% of the total surface of the area.

This classification may lead to a situation where an area is classified as 100% urban, while an areal photograph still shows, e.g., some grassland. An example and further explanation on the classification is in the supporting information.

Land use data within a 10 km radius circles around each European Climate Assessment and Dataset (ECA&D) meteorological station are extracted from the CORINE data set. The 10 km radius is much larger than the typical distance over which the UHI effect extends over a heterogeneous landscape, which is closer to 1 to 5 km [*Suomi et al.*, 2012]. To classify the stations, the urban percentage of the area around each station was calculated for the 10 km radius but also for smaller circles with radii of 5, 2.5, and 1 km.

2.2. Air Temperature Data Set

The ECA&D (European Climate Assessment and Dataset) [*Klein Tank et al.*, 2002] is a collection of daily station observations, not adjusted for urbanization, and is the basis for the E-OBS gridded data set [*Haylock et al.*, 2008], providing daily gridded temperature over the period 1 January 1950 to the present. A European-averaged temperature is calculated using the gridded data; calculating a European temperature using station data directly would bias the result toward areas with high station densities.

Information on the urbanization in some eastern European countries lacks in CORINE. The eastern boundary of the domain over which the European temperature is calculated therefore coincides with the eastern borders of Finland and Poland and from there along 25°E into the Mediterranean (instead of having the border at 45°E as in *van der Schrier et al.* [2013]).

Further details on the calculation of the European temperature are documented elsewhere [*van der Schrier et al.*, 2013].

3. Classification of Stations

3.1. Urbanization Levels for European Stations

For CLC2006, the urban percentage in circles with radii of 1, 2.5, 5, and 10 km around each station was calculated. Table 1 shows the urbanization percentage of the 3410 temperature-providing stations, which are both in ECA&D and in countries which participate in CLC2006, as a function of radius. For the 10 km resolution there are only four stations with an urban percentage above 80% with station Hampstead (London) having the highest value of 85.3%.

Perhaps, a more appropriate way of quantifying the effects of urbanization around a station is to aggregate the urban area in the segment of the circle upwind of the station. The lack of a sufficiently dense network with anemometers in ECA&D prohibits this approach.

With increasing radius, the number of stations with high urban percentage decreases. The range with 0–10% urban percentage holds 75% of meteorological stations available in ECA and D. For each radius, the highest

Table 1. Number of Stations as a Function of Percentage Urban Area in Areas Surrounding Meteorological Stations With Radii of 1, 2.5, 5, and 10 km

Percentage (%)	1 km	2.5 km	5 km	10 km
0	1168	789	537	327
0.01–10	327	966	1572	2220
10–20	372	502	579	511
20–30	257	369	308	153
30–40	279	261	175	88
40–50	234	186	106	51
50–60	201	135	50	37
60–70	161	71	38	16
70–80	145	66	27	3
80–90	143	45	16	4
90–99.9	91	20	2	0
100	32	0	0	0

number of stations is in the 0–10% urban percentage range. A large number of stations, albeit still a minority, (1168, 34%) have no urban fabric at all in the 1 km radius. This shows that most of the meteorological stations in ECA&D are located in areas with low levels of urbanization. Nevertheless, urbanization effects cannot be ruled out.

3.2. Rural Stations

Stations are classified using urbanization percentages from the circles with 1, 2.5, 5, and 10 km radii surrounding the stations. A weighted sum of these percentages gives an "urban index" R:

$$R = aU_{10\,\mathrm{km}} + bU_{5\,\mathrm{km}} + cU_{2.5\,\mathrm{km}} + dU_{1\,\mathrm{km}}, \quad (1)$$

where $U_{10\,\mathrm{km}}$ is the urban percentage in a circle around a station with a 10 km radius (analogous for the other variables). In order to determine the coefficients in (1), a subset of approximately 100 stations in ECA&D is classified using aerial photographs from Google Earth and the quantitative information from CLC2006 as either rural or urban. With the transition from urban to rural environments often as a continuum rather than having a clear demarcation between the two, stations not clearly at either ends of the urban-rural spectrum were classified as suburban. These were supplemented by stations which are classified in the literature as being in the transition zone, like De Bilt (Netherlands) [*Brandsma et al.*, 2003] (see the supporting information).

A least squares fit of the coefficients in (1) with the classification described above gives $a = 1\%^{-1}$, $b = 0.7\%^{-1}$, $c = 0.2\%^{-1}$, $d = 0.5\%^{-1}$, and classification boundaries $R > 110$ for urban stations and $R < 20$ for rural stations. According to this criterion, 166 (5%) stations are urban and 1681 (49%) stations are rural.

The visual classification of stations is subjective; the approach is therefore supplemented by two other, more quantitative, approaches.

3.3. Low-Growth Stations

A second approach to classify stations relates to the growth of the urbanization surrounding a station. This growth is quantified by comparing urban percentages for each station from the three available versions of the CORINE project.

Table 2. Change in Urban Percentage Between Two CORINE Data Sets[a]

Change in Urban Percentage (%)	2006–1990	2006–2000	2000–1990
0	208 (1189)	975 (1367)	8 (22)
1–2	1392 (162)	548 (75)	21 (2)
3–4	150 (145)	10 (31)	0 (3)
5–6	24 (87)	2 (16)	0 (1)
7–8	21 (74)	1 (12)	0 (0)
9–10	7 (47)	0 (11)	0 (0)
11–20	10 (75)	0 (19)	0 (1)
21–30	0 (25)	0 (3)	0 (0)
31–80	0 (8)	0 (3)	0 (0)
Stations in total	1812	1537	29

[a]Areas used are the 10 km circles around each station (values for 1 km between brackets). If a country did not participate in CLC90 or CLC2006, the difference with CLC2000 is used.

In CLC90 25 countries participated having in total 1927 stations in ECA&D, in CLC2000 35 countries participated resulting in 3444 stations, and in CLC2006 38 countries and 3410 stations. Switzerland participated in CLC2006 only, making it impossible to calculate a change in urbanization using CORINE for the Swiss stations. This makes that in this approach, not all available stations can be classified.

Comparing urbanization percentages based on the CLC90 and the CLC2006 shows that most of the stations have a difference between 0.1 and 1% of urbanization in a 10 km radius. Only 10 stations have a change in the

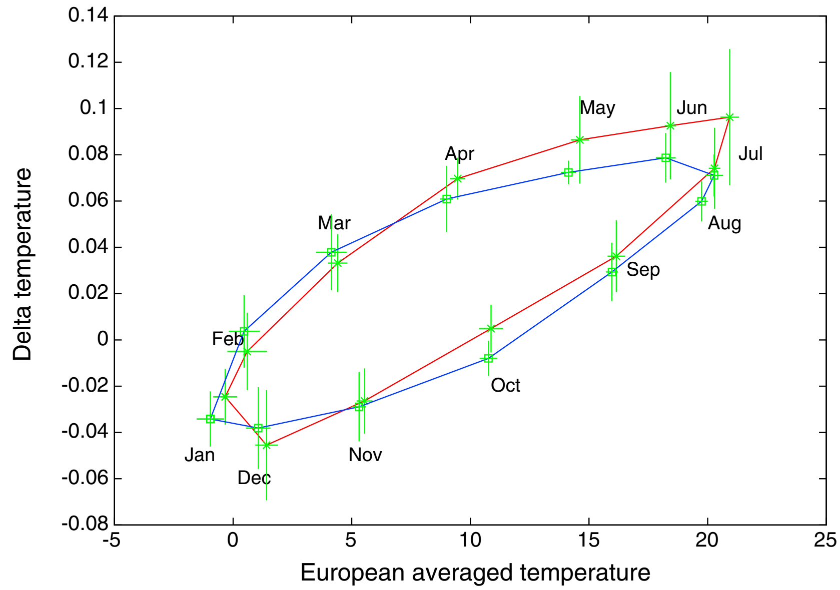

Figure 1. Seasonal cycle in urbanization-related warming averaged over Europe (vertical), based on the selection of rural stations only (§ 3.2), versus the European-averaged temperature based on all stations (horizontally). The blue curve is based on data from the period 1960–1979; the red curve uses data from 1991 to 2010. The figures show a clockwise hysteresis loop. Green whiskers give the 1 standard deviation variation. All units are degree Celsius.

range of 10 to 20%. For a 1 km radius, most stations (65%) did not see a change at all in urbanization. However, the immediate surroundings of a few stations changed significantly. Comparing CLC2000 and CLC2006 for the stations in the countries that did not participate in CLC90, most of the stations had no change at all (Table 2). Relative growth G is calculated as the difference in the percentage of urbanization between 2006 and 1990, divided by the 2006 level (with appropriate replacements and corrections when one of the urbanization levels is missing). Low-growth stations are defined in this study as stations with G lower than 0.1, which is an ad hoc value.

3.4. Stations With Small Temperature Trends

To identify the urbanization-affected stations based on temperature trends rather than on land cover characteristics, stations with small temperature trends are contrasted against the full set of stations, removing those potentially affected by urbanization trends. The station with the strongest temperature trend within a rectangular box of 5° × 10° (latitude, longitude) is identified. The stations that enter the selection are those stations that have annual temperature trends over the 1981–2010 period that are less than 75% of this highest value, ignoring the stations that have strong temperature trends in this period or stations that are too incomplete for trend calculation. The 1981–2010 period is chosen because this is a period with strong changes in temperature. This resulted in a set of 2603 stations.

4. Results for the European Temperature

For each of the three subsets of stations, a daily gridded data set is produced, averaged to a monthly level and subsequently averaged over Europe. This is compared with the European-averaged temperature based on all available ECA&D stations. The gridded temperature based on a less dense network will have more areas without data than the one based on the full set of stations. A possible bias is removed by making sure that both gridded data sets share the same mask of missing and nonmissing grid squares.

Figure 1 shows the urbanization-related warming (based on the selection of rural stations only, section 3.2) against the European-averaged temperature (using all stations) stratified by month. It shows that the pan-European urbanization-related warming has a distinct seasonal cycle and follows a hysteresis loop with the urbanization effect weakest in winter and strongest in summer and with very different amplitudes in spring and autumn. The rotation of the loop is clockwise, indicating that in a pan-European sense, urban areas warm faster than the rural areas in spring and cool down quicker in autumn. Similar

Table 3. Difference in Trends Between European-Averaged Temperature Based on All Available Stations and Based on Subsets of Stations Over the Period 1960–2012 in °C/Decade[a]

	Annual	Winter	Spring	Summer	Autumn
Rural stations	**0.0025**	−0.0009	**0.0028**	**0.0069**	0.0014
Low-growth stations	0.0019	−**0.0049**	0.0019	**0.0095**	0.0011
Low-temperature trend stations	0.0032	0.0028	0.0030	**0.0045**	0.0025
Average	**0.0026**	−0.0010	**0.0026**	**0.0070**	**0.0017**
1960 level	0.0115	−0.0091	0.0267	0.0321	−0.0032

[a]The last line shows the 1960 level of urbanization-related warming using rural stations only. Trends are calculated using linear least squares; bold numbers indicate significance at the 95% level using an estimate of the number of degrees of freedom in the presence of autocorrelation.

behavior can be observed by comparing station data from stations inside and outside selected cities (see the supporting information).

The strongest effects of urbanization on the trend in the European-averaged temperature are in spring and summer (Figure 1), visualized by the difference in seasonal cycle for data averaged over the 1960–1979 period (blue curve) and 1991–2010 (red curve). Table 3 shows a trend in summer temperature related to urbanization, averaged over the three estimates of the European temperature, of 0.0070°C/decade which is more than twice the trend we find in annual values (0.0026°C/decade). The trend in the urbanization-related warming over Europe (annual average) is largest for the data set based on the stations with the small temperature trends. Apparently, the threshold used in the selection criterion is such that this is an estimate of the rise in temperature due to pan-European urbanization which is at the high end.

Figure 2 shows annual averages of the European-averaged temperature (top) and the difference between the version based on all stations and the three subsets of stations for the period from 1960 onward (bottom). There are only small differences between the estimates of the European temperature, with the subset using rural stations only (section 3.2) having a maximum difference of 0.0556°C in 2009. With

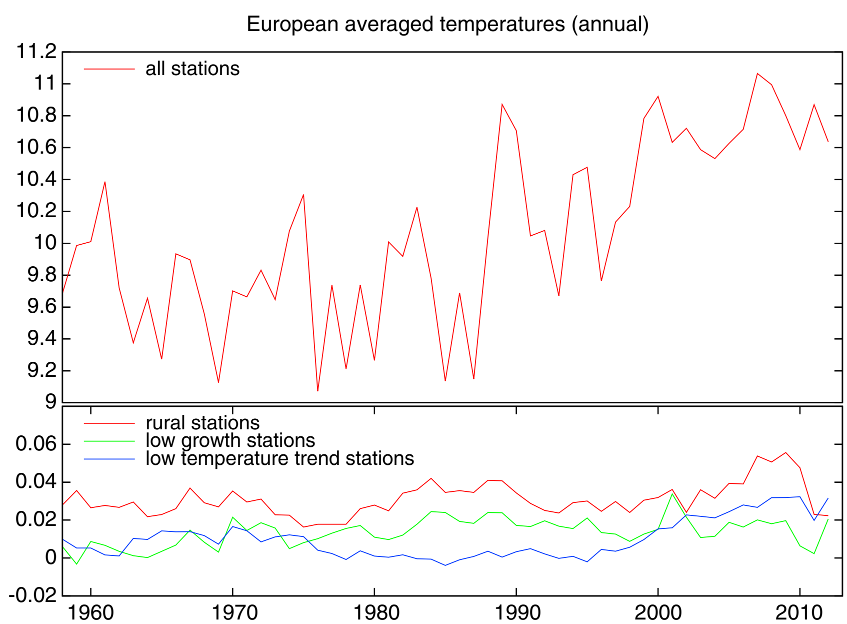

Figure 2. (top) European-averaged annual temperature based on a grid using all meteorological stations. (bottom) The difference series between the European-averaged temperature based on all stations and based on the rural stations only (red), the low-growth stations only (green), and the one based on stations with small temperature trends (blue).

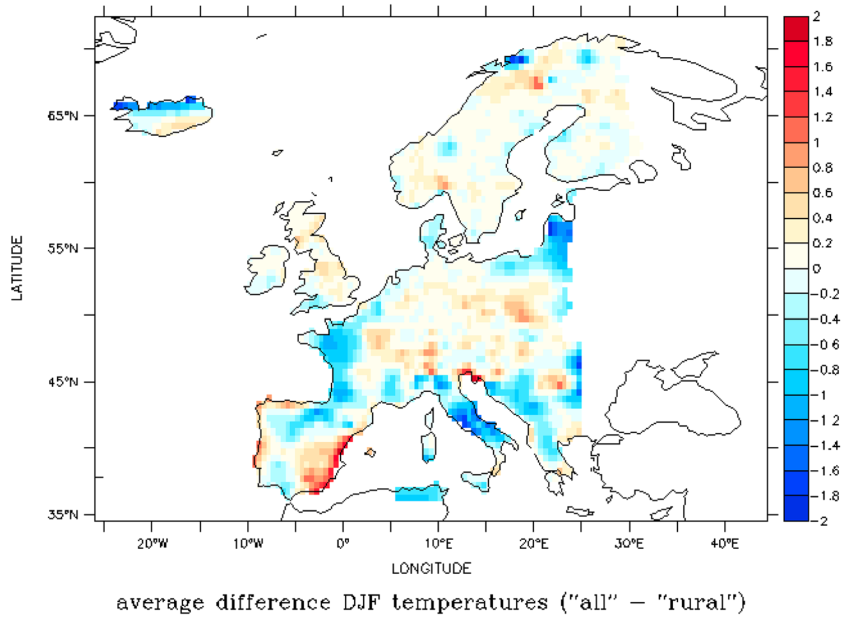

Figure 3. Map of winter temperature difference between the estimate using all available stations and the estimate based on the rural stations only (as classified in section 3.2).

only a few exceptions in the earlier part of the record, the European-averaged temperature of the data set based on all available stations is higher than the ones based on the subsets of stations as grouped in sections 3.2, 3.3, and 3.4.

The 1960 level of the urbanization-related warming is difficult to estimate reliably. When gridding data from a network which excludes urbanization-affected stations, the search radius will be larger than with high-density networks. In the presence of strong spatial temperature gradients, like near the coast, cold inland temperatures may then be used to estimate temperature in a grid square, replacing warm coastal temperatures from stations which happen to be in an urbanized area. This effect also occurs in areas near the eastern domain boundary, like in Latvia, by mixing-in temperatures from colder, more eastery-located stations. Figure 3 shows a map for the urbanization-related warming in winter (averaged over the period 1960–2012). In winter, this artifact is most visible in an inverted urbanization effect (i.e., urbanization gives a cooling). This should not be interpreted as a real physical phenomenon. Estimates of the trend in pan-European temperature due to urbanization will not be affected, but this phenomenon handicaps a reliable estimate of the absolute urbanization-related warming. Nevertheless, these values for the year 1960 are given in Table 3.

5. Discussion

A classification is made of the meteorological stations included in ECA&D in terms of their rural character, using three different approaches, and shows that the vast majority of stations are in rural surroundings and have seen no or little change in urbanization over the recent past.

The estimate of the European-averaged Urban Heat Island effect shows a distinct hysteresis-like seasonality, with highest values in summer and lowest values in winter. Also, the trends in European-averaged temperature related to urbanization have a strong seasonality, with summer having the highest trends. The annual-averaged value of the urbanization effect on temperature is lower than the value used in earlier work, but the assumption of a lack of seasonality is clearly untenable.

The hysteresis behavior of urbanization-related warming has recently been observed by *Zhou et al.* [2013] using satellite-sourced temperature data for clusters of cities in Europe and is reproduced here using air temperatures averaged over Europe.

In closing, it must be readily admitted that a move of a station from urban to more rural surroundings may be unnoticed if this move is not documented in the metadata available at ECA and D. Imprecise information on the location of a station may occur as well, both may lead to erroneous classification of stations.

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