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# Influence of synoptic scale atmospheric circulation on the development of urban heat island in Prague and Bucharest

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ABSTRACT

This study has analysed the development of the urban heat island (UHI) under various synoptic scale atmospheric circulation for two large cities – Prague in central Europe and Bucharest in south-eastern Europe, including seasonal differences and long-term changes. At the best of our knowledge, it is the first comparison between two European cities from this perspective. Analysis was conducted on the base of minimum air temperature data from pairs of urban and peri-urban stations. The average UHI intensity is 2.3 °C for Prague and 1.8 °C for Bucharest, it exceeds 4 °C in 6–10% of cases, and the highest values occur in August in both cities. The annual course of monthly mean values of UHI intensities has higher amplitude in Bucharest (1.2 °C) than Prague (0.6 °C). Synoptic scale circulation is classified according to mean sea level pressure data from ECMWF Era-Interim reanalysis using cost733class software. The results show that UHI is more intense under anticyclonic situations with southern winds in the both cities. Over 1981–2016, we found that the UHI intensity followed statistically significant increasing trend, much larger trend for Bucharest than Prague (3.3 °C vs. 1.3 °C / 100 years).

## 1. Introduction

Urban heat island (UHI) is a phenomenon occurring at the crossroad between the metropolitan areas and regional climate, consisting of a significantly higher city temperature in respect to the surrounding peri-urban and rural neighbourhoods. The reasons for the UHI occurrence are relatively well understood (e.g. Landsberg, 1981; Oke, 1982; Arnfield, 2003), and the effect of meteorological parameters on UHI magnitude was the subject of considerable research (Sakakibara and Matsui, 2005, Park, 1986, Stewart, 2011; Hove et al., 2015.

Since the intensity of the UHI largely depends on the size and population of the cities, one can expect an increasing UHI intensity in the coming years due to the foreseen growing of population living in urban areas. The effect of the UHI will very likely increase the adverse effect of heat waves which are expected to become more frequent as the result of global warming Founda and Santamouris (2017). Consequently, its impact on different sectors e.g. health, transportation or building industry will be higher.

The development of the UHI is strongly influenced by synoptic circulation. The anticyclonic conditions are generally more

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favourable because of higher direct radiation due to lack of cloudiness and weak winds (Morris et al., 2001). However, even under anticyclonic conditions low cloudiness can develop and hinder the "radiation weather" in the city. Wind can be quite strong, destroying or barring the UHI development. Therefore, the influence of the anticyclonic conditions on UHI are different according to the geographic position of the anticyclone and prevailing wind direction (Morris and Simmonds, 2000). The lowest UHI magnitude does not necessarily occur under cyclonic conditions. Many papers focus on the optimal conditions for UHI development, such as clear sky, and weak wind, or describe its average features, while the number of studies dealing in depth with the relationship between the UHI magnitude and various synoptic conditions is considerable smaller (e.g. Beranova and Huth, 2005; Półrolniczak et al., 2017).

In the central and south-eastern Europe, the influence of the synoptic conditions on the UHI characteristics was studied for medium-size cities, e.g. Szeged (Unger, 1996) and Debrecen in Hungary (Szegedi and Kircsi, 2003), or Poznań in Poland (Półrolniczak et al., 2017), as well as for large cities e.g. Athens, Greece Mihalakakou et al., 2004), or Augsburg, Germany (Beck et al., 2018). These studies used data from measuring campaigns with the advantage of large spatial coverage, but at short time span (2 to 6 years), unsuitable for capturing climate trends or long- term behaviour of UHI. Beranova and Huth (2005) studied the UHI of Prague over 1961–1990 period, based on the Bradka synoptic catalogue,[1] which uses the cyclonic/anticyclonic and directional characteristics (Bradka et al., 1961). The results showed that the North to North-East and South to South-West synoptic flows amplify the Prague's heat island. However, the results may be biased because the use of the Bradka synoptic catalogue is limited to central Europe.

The main objective of this paper is to characterize the development of the UHI under various synoptic scale atmospheric circulation for two large cities – Prague, in Central Europe – and Bucharest – in South-Eastern Europe. The analysis includes seasonal differences and long-term changes. The comparison of two cities placed in different geographic conditions can enhance our understanding in UHI formation and may facilitate the transfer of the results to other areas.

## 2. Study areas

The selection of Prague and Bucharest is motivated by the similarities in their physical-geographical background. Both cities are situated in large depression-like structures (Bohemian Depression for Prague and Romanian Plain for Bucharest) surrounded by mountain barriers around at 100 to 200 km distance, which shapes the atmospheric circulation at synoptic scale (i.e. Krusne hory/ Erzgebirge and Krkonose to the west to north, and Sumava to the south from Prague, and Carpathians, to the north to west and Balkan Mountains, to the south of Bucharest).

### *2.1. Prague*

Prague is the most populated and the capital city of the Czech Republic settled along both sides of the Vltava river. The distribution of green infrastructure (i.e. parks and woods) is quite non-uniform, with generally more green areas situated in the southwestern part of the city.

The climate of Prague is mild and transitory between maritime and continental with thermal continentality according to Gorczyański 26–27% (Kveton and Zak, 2007), the multiannual thermal amplitude is 28.7 °C, with mean daily minimum temperature of −3.6 °C in January and mean daily maximum temperature of 25.1 °C in July (Table 1).

The territorial development of Prague has led to continuous spread of built up areas and change in land cover types from green/ agricultural to built-up (e.g. flats, factories, commercial and transport areas) parallel with increase of the population (i.e. from one million at the end of the 1940s to approx. 1.3 million nowadays). Two periods of important changes of the land cover types may be delimited, namely the period 1960–1980 and the period after 1990, defined by the transformation of economy from state controlled economy to market economy, when almost 2% of „green "areas was converted into built-up categories (Environment Portal of Prague, 2020). Nowadays green areas (parks, gardens, woods, grass areas) represent approx. 25% of the city. The role of this green areas on the UHI is not very strong, since the larger regions of greenery are situated mostly in the outer parts of the city having only limited influence – mainly in reducing the size of the UHI of Prague (Huszár et al., 2014). The historical densely built-up centre is surrounded by scattered forms of houses usually having 4 to 8 floors, partly modern partly almost 100 years old. Further, large areas of blocks of flats built in the period 1960–1980 mixed with modern high-rise buildings (often office buildings) arise. Details on land use of Prague can be seen on Fig. 1.

### *2.2. Bucharest*

Bucharest has about 2 million permanent residents, and it is situated in the south-eastern part of Romania, along the Dâmbovița River. The climate is characterized mostly by moderate continental features with a multiannual thermal amplitude of 48.4 °C, mean daily minimum temperature of −11.9 °C in January and mean daily maximum temperature of 36.5 °C in July (Table 1).

The city has a highly disruptive urban architectural structure as a result of different political regimes and planning strategies. Single- or two story-houses, often surrounded by small gardens are characteristics for the 19th century part of the city. Between the two world wars, taller buildings were erected, usually with 3–8 storeys, setting better the urban profile of the epoch. Abrupt changes occurred during the socialist period (1950–1989), and especially in the eighties, when built-up areas replaced many green areas, and the height profile of the city changed dramatically. Compact areas built after the devastating earthquake that hit Bucharest in 1977

[1] http://portal.chmi.cz/historicka-data/pocasi/typizace-povetrnostnich-situaci#

**Table 1**
Comparison of main geographic and meteorological characteristics of Prague and Bucharest.

| | Prague | Bucharest |
|---|---|---|
| General characteristics | | |
| Area | 496 $km^2$ | 240 $km^2$ |
| Population | 1,300,000 | 2.104.967 |
| Average altitude above sea level | 235 m | 72 m |
| Altitudinal range | 180–395 m | 54–90 m |
| Size of green areas | 25% | 12% |
| Meteorological characteristics | | |
| Annual average temperature | 8.9–10.8 °C | 11.6 °C |
| July average temperature | 20.8 °C | 23.4 °C |
| January average temperature | 0.9 °C | −0.7 °C |
| Annual average precipitation | 500 mm | 603.3 mm |
| The driest month | February (20 mm) | February (35.6. mm) |
| The wettest month | June (70 mm) | June (78 mm) |

have 4 to 10 story-buildings and they are widespread over the city. After 1990, the building profile have gradually changed. The central part of the city became more compact, and the city extended over the marginal neighbourhood, sometimes at the expense of significant green areas, such Băneasa Forest, in the northern part of the city.

Currently, the urban area of Bucharest includes 7 urban lakes covering 46.9 ha, while other 9 "outer", can be found in the neighbouring rural areas, comprising 1044.9 ha. Cheval and Dumitrescu (2015) linked the formation of the Bucharest summer surface UHI to the land cover (Fig. 2) and emphasized the role the urban blue infrastructure in alleviating the UHI impact. For example, In July, the daytime land surface temperature is with 2–3 °C lower over inland waters than over urban fabric.

## 3. Data and methods

Traditionally, the UHI intensity is calculated as a difference between urban and rural air temperatures, and it depends on factors such as the size of the city and its population, topography, climate zone and meteorological conditions (Oke et al., 1991).

The UHI intensity for the two cities was computed based on pairs of stations. For Prague, we used the weather stations Klementinum, situated in the historical centre (191 m a.s.l., 50°05′1"N, 14°24' E), with the highest annual average temperature in the Czech Republic (10.2 °C for period 1961-2000), and Kbely, situated at the military airport (284 m a.s.l., 50°7'25"N, 14°32′E) as a rural station. Kbely is still within the Prague metropolitan area, but due to its peripheral location with flat, open fields enclosed by green and agricultural terrain, it is treated as a reference station for UHI analysis. For Bucharest, the weather stations București-Filaret (82 m above sea level) in the city centre (44° 24′ 44" N, 26° 05' E), and București-Băneasa (90 m a.s.l.) in the northern outskirts of the city (44°30' 39.95" N, 26° 05′ E) were used. București-Filaret station is placed in an urban park, and Băneasa is situated in an area with intense changes, such shifting from green to built-up spaces, which occurred after 2000. The distance between the rural and urban stations is about 10 km both for Prague and Bucharest (Figs. 1 and 2).

This study focuses on the daily minimum temperatures, as UHI is usually more intense at night-time (Martinez et al., 1991; Unger, 1996; Montavez et al., 2000; Sfîcă et al., 2017; Karlický et al., 2018), and the GrossWetterTypen (GWT) classification scheme of atmospheric circulation based on threshold criteria (Beck, 2000; Beck et al., 2007). This classification is based on daily mean sea level pressure (MSLP) at 12:00 UTC data from ECMWF Era-Interim reanalysis (Dee et al., 2011), using cost733class software (Philipp et al., 2014). The GWT classification characterizes the circulation patterns in three terms of varying degrees of zonality, meridionality and vorticity of the large scale MSLP field. The first one is based on MSLP values increasing from North to South; the second denotes the MSLP increasing from West to East, while the third type denoted the cyclone pattern with pressure values increasing from the baric centre to the outer isobars. Based on the correlation between each input field (i.e. MSLP) and the predefined types, a day is automatically assigned to a class However, the term "objective" is arguable, since the decision for thresholds and criteria still involves subjective decisions. The reproducibility and the fast processing are still important advantages of the GWT classification scheme.

In order to clearly separate the atmospheric circulations types (CT), we have used 18 types, divided in 8 cyclonic, 8 anticyclonic, and 2 types for centre low and centre high situations, as derived from the surface pressure field. The description of all types can be found in Table 2. The overview of the CTs, based on centroids showing the MSLP spatial distribution (Fig. 3), and the frequency and average persistency of each CT (Table 3) show the average synoptic context of the analysed cities.

Fig. 4 illustrates the mean deviation of daily minimum temperatures for all CTs against the multiannual mean, as derived from ECA&D dataset (Haylock et al., 2008). For both cities, the highest positive deviations occur under Ec, SEc and NWa. The largest negative values usually occur under NEa, SWc and Sa types, for Bucharest also during type Ea. In order to increase the sample size for further analyses, the circulation types were divided in two larger groups according to their (anti)cyclonic patterns. Further, these two groups were divided by their mean advection trajectory towards the centre of the domain assessed by the U and V 10 m-wind components retrieved from ERA Interim (Dee et al., 2011). At the end, four circulation classes resulted, as follows: (1) southerly cyclonic, (2) southerly anticyclonic, (3) northerly cyclonic, and (4) northerly anticyclonic (Fig. 2). We preferred to group the circulations into four groups (cyclonic/anticyclonic; northerly and southerly) since this would be easier to interpret the results in the terms of airflow directions.

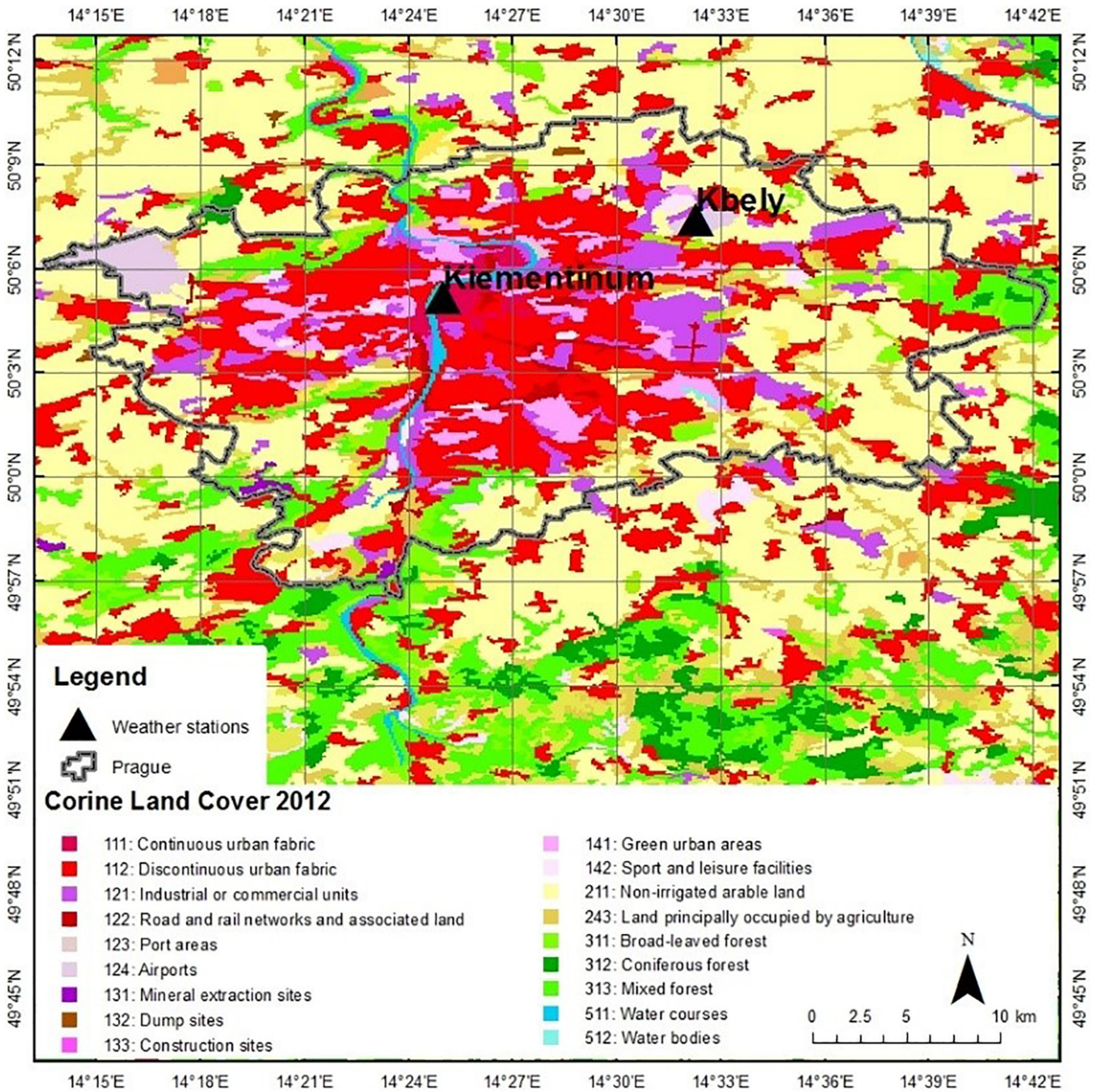


**Fig. 1.** Land cover map of Prague and weather stations used for this study (source: European Environment Agency - https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012).

In this manner, a western or an eastern circulation type was also grouped into a northern/southern type depending on the predominant mean wind direction for that type. For example, if a circulation had a northwest wind direction, it was labelled as being a northerly (cyclonic or anticyclonic) type. Also, if the airflow had a clear west/east direction, we considered the location of the pressure system imprinting the wind direction. For example, if a high-pressure system was located in the southwestern Europe and the wind direction for Prague (or Bucharest) was predominantly from the west, the circulation was labelled as south anticyclonic. The GWT catalogue provides the CTs for the period 1981–2016.

## 4. Annual and seasonal regime of the UHI intensity in Prague and Bucharest

Downtown areas are warmer than the outskirts, both for Prague (99% of the total number of nights) and Bucharest (87%), outlining a very clear night-time UHI (Table 3). The differences between the urban and rural areas are mostly less than 2.5 °C, but under convenient circumstances, they can raise up to 8 °C. The situations with night-time UHI intensity higher than 1 °C is 92% for Prague and 59% for Bucharest, while situations with UHI intensity over 3 °C occur in 22% for Prague, and 25% for Bucharest. The

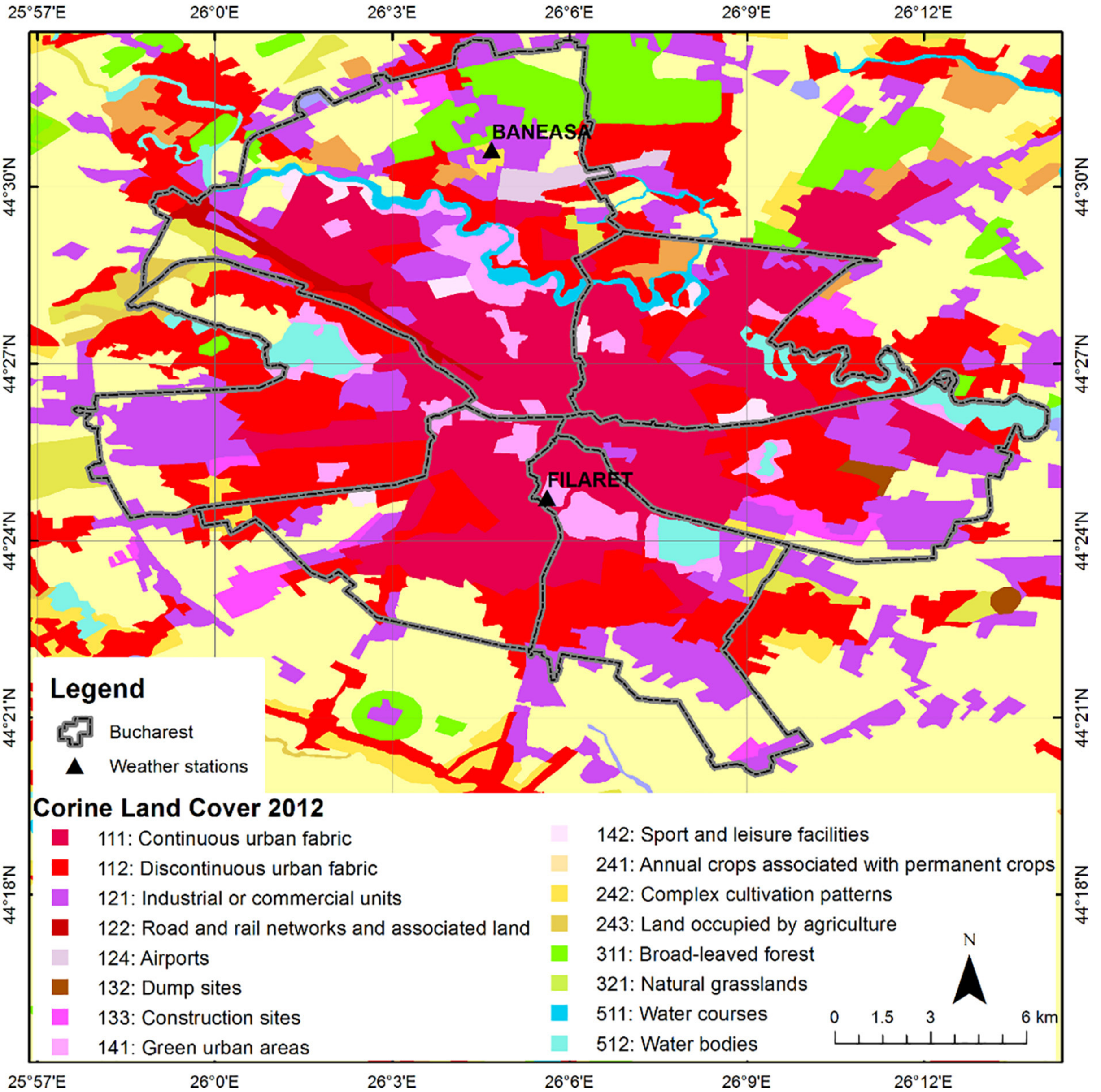


**Fig. 2.** Land cover map of Bucharest and weather stations used for this study (source: European Environment Agency - https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012).

situations with UHI intensity over 4 °C can be called as an "extreme" UHI. For these situations, an overview is given in Table 4. The relation between cyclonic or anticyclonic weather types and "extreme" UHIs shows that, generally, very strong nocturnal UHIs are more often in Bucharest than in Prague (i.e. 10%, respectively 6%), and they occur more frequently under anticyclonic weather conditions for all seasons in both locations. There are clear seasonal differences between Bucharest and Prague in respect of "extreme" night-time UHI situations. In Bucharest they occur most often in spring and summer, and rarely in winter, while for Prague the highest frequency of the very intense nocturnal UHIs is in winter and spring, while in summer they happen less often.

The UHI is a dynamic phenomenon, with relatively high seasonal variability. The highest monthly average of UHI intensity occurs in August for both cities, while the lowest values can be found for Prague during November and December, and for Bucharest during December and January (see Fig. 5). The larger UHI intensity occurs in Prague (annual average 2.3 °C) than for Bucharest (1.8 °C), but the annual amplitude of the monthly UHI intensity is almost double in Bucharest compared to Prague (i.e. 1.2 °C vs 0.6 °C). This can be caused by the geographical configuration of the compared cities. Bucharest is placed over a relatively flat area, with less than 100 m altitudinal range, while Prague is cut by the Vltava river, with more than 100 m altitudinal amplitude. The historical downtown Prague is very densely built up leading to less intense cooling during winter nights compared to the rate of cooling at

**Table 2**
Synoptic scale weather circulation types and groups, their persistency and frequency.

| Code | Circulation Type | Description | (Anti)cyclonic group | Groups | Persistence | Frequency |
|---|---|---|---|---|---|---|
| 1 | Nc | Northern cyclonic | Cyclonic | Southerly Cyclonic | 1.1 | 337 |
| 2 | NWc | Northwest cyclonic | Cyclonic | Southerly Cyclonic | 1.2 | 461 |
| 3 | NEc | Northeast cyclonic | Cyclonic | – | 1.0 | 220 |
| 4 | Ec | East cyclonic | Cyclonic | Notherly Cyclonic | 1.2 | 297 |
| 5 | SEc | Southeast cyclonic | Cyclonic | Notherly Cyclonic | 1.4 | 508 |
| 6 | Sc | South cyclonic | Cyclonic | Notherly Cyclonic | 1.5 | 581 |
| 7 | SWc | Southwest cyclonic | Cyclonic | – | 1.4 | 491 |
| 8 | Wc | West cyclonic | Cyclonic | Southerly Cyclonic | 1.3 | 460 |
| 9 | Sa | South anticyclonic | Anticyclonic | – | 1.5 | 1359 |
| 10 | SEa | Southeast anticyclonic | Anticyclonic | Southerly Anticyclonic | 1.4 | 1032 |
| 11 | SWa | Southwest anticyclonic | Anticyclonic | – | 1.4 | 1156 |
| 12 | Wa | West anticyclonic | Anticyclonic | Northerly Anticyclonic | 1.4 | 1061 |
| 13 | NWa | Northwest anticyclonic | Anticyclonic | Northerly Anticyclonic | 1.6 | 1086 |
| 14 | Na | North anticyclonic | Anticyclonic | – | 1.6 | 994 |
| 15 | NEa | Northeast anticyclonic | Anticyclonic | – | 1.5 | 706 |
| 16 | Ea | East anticyclonic | Anticyclonic | Southerly Anticyclonic | 1.4 | 656 |
| 17 | L | Central Low | Cyclonic | Southerly Cyclonic | 1.2 | 335 |
| 18 | H | Central High | Anticyclonic | Northerly Anticyclonic | 1.4 | 1409 |

București-Filaret, the urban station used for Bucharest, placed in a park. This is consistent with the demonstrated different behaviour of urban compact areas, such as Klementinum station in Prague, and less built-up areas, such as urban parks or smaller buildings, such as București-Filaret (Cheval and Dumitrescu, 2017). The climate continentality is more pronounced in Bucharest than in Prague (Cheval et al., 2017) triggering a higher temperature variability during the year, and the UHI follows the same pattern.

## 5. UHI intensity in Prague and Bucharest under various synoptic circulation types

The average annual intensity of the nocturnal UHI was computed for all individual circulation types for both cities (Fig. 6). As expected, the UHI is stronger developed under weather types characterized by high radiation, low wind, and minimum cloudiness. For Prague, the highest intensity of UHI is observed under H type (2.8 °C) following by NEa type (2.7 °C), with prevailing south- to south-westerly wind, i.e. warm air with anticyclone conditions. For Bucharest, the situation is slightly different; the largest UHI occurs for the L circulation type (2.2 °C) that has actually only small frequency, followed by Ea type (2.1 °C). While this is quite reasonably for Ea (southerly wind component, more or less anticyclonic circulation, i.e. suitable conditions for UHI development), large UHI intensities for cyclonic low (L) are less expected, since this weather pattern consists of a low- pressure system upon Central Europe extended over the western Romania as well (i.e. less suitable for UHI development). The lowest intensity of UHI can be observed under Nc type for Prague (around 1.8 °C) connected with higher pressure gradient over Czech Republic and wind from North Atlantic bringing more cloudiness. For Bucharest, the UHI is less developed under SWc circulation type (1.1 °C), reflecting the cyclogenesis conditions in the northern Adriatic Sea. This weather pattern is accompanied by cyclonic trajectories and it is responsible for rainy weather over the Balkan Peninsula and Romania.

The annual regime of the UHI was investigated based on the directional groups of CT (see Table 5) to have the similar circulation types in homogenous groups. The maximum UHI can be found for winter season in Prague except for SA group where a bit larger value is observed in spring (although differences between seasons are not too large, usually smaller than 0.3 °C, see Fig. 7). For Bucharest different results can be found with largest intensities occurring during summer (Fig. 8). There are larger differences among seasons for individual groups and seasons compared to Prague, as well. During the summer, the Azores High western ridge is extended towards the eastern Mediterranean delivering southerly air advection for southern Europe. As a consequence of air stability associated to high pressure systems, the summer cloudiness is lower than in the other seasons, leading implicitly to greater direct radiation values.

The lowest UHI intensity for Prague occurs in summer, but not for all directional groups, i.e.NC is smallest in autumn, while for Bucharest, for all directional groups, the lowest intensity happens in winter (Fig. 8).

## 6. Decadal variability of the UHI

Due to various factors like population increase, enlargement of built up areas and associated development of transport, energy consumption or industrial activities, the UHI can often increase along time. The statistical significance of the linear trends of the UHI intensity variability over 1981–2016 was tested with AnClim software (Stepanek, 2008) at 95% confidence level by the Mann-Kendall test. Increasing trends of UHI intensity are revealed for both studied cities, at a higher rate for Bucharest (Table 6). The trends differ for different seasons and directional groups. The highest increase in Prague occurs during winter season, especially for SA and SC groups, very likely in connection with more often snowless situations occurring in the city centre of under warming climate and more intense UHI development. It is worthy to be noted that trends for NC group are not statistically significant in Prague. For Bucharest, the largest increase can be found during spring, especially for SC group, and for summer days within SA group (above 4 °C

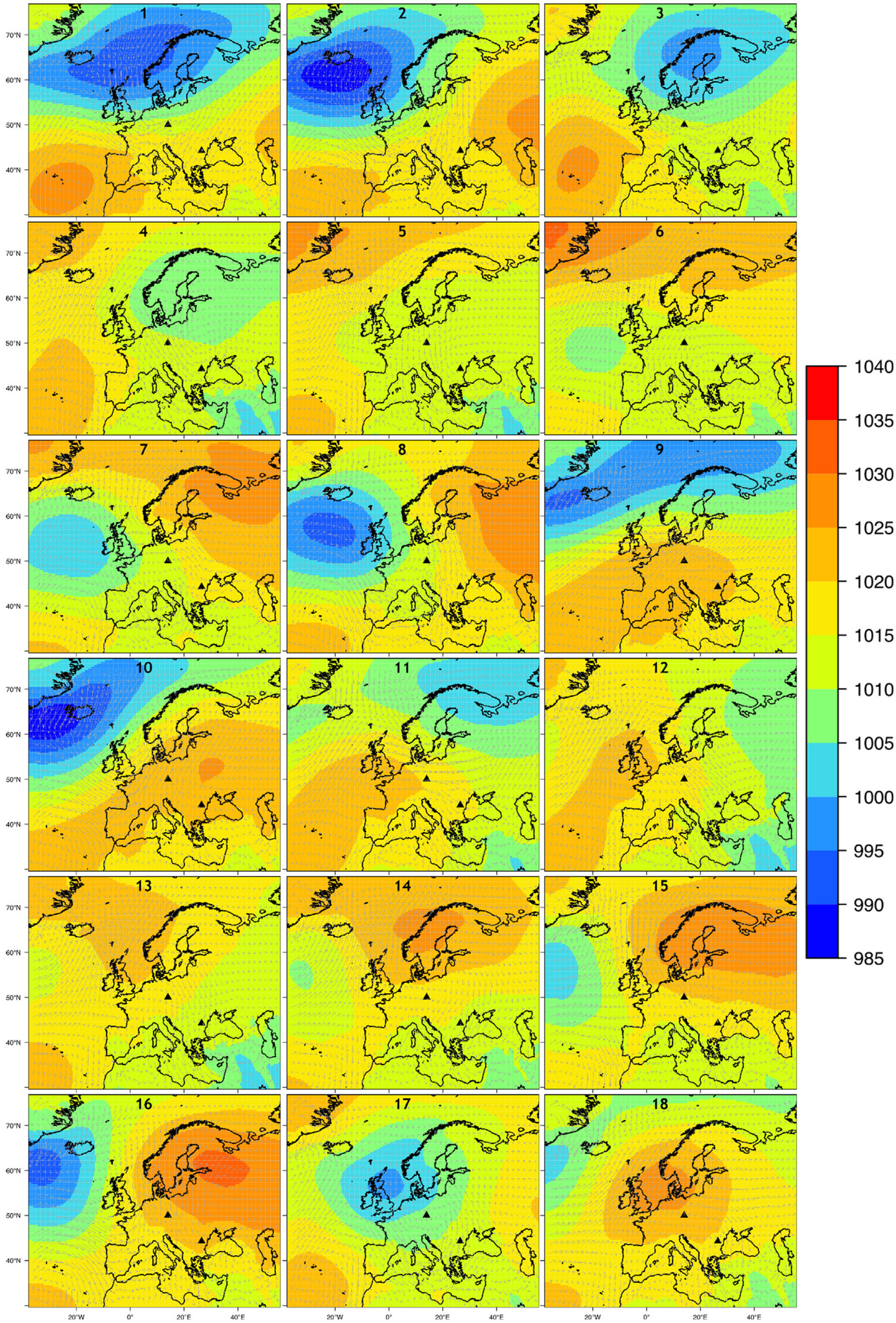


**Fig. 3.** Weather types based on CT classification scheme (using GWT classification (Beck, 2000).

**Table 3**
Percent of days with given UHI intensity for Prague and Bucharest.

| UHI intensity | 0–0.5 °C | 0.5–1.0 °C | 1.0–1.5 °C | 1.5–2.0 °C | 2.0–2.5 °C | 2.5–3.0 °C | 3.0–3.5 °C | 3.5–4.0 °C | over 4 °C |
|---|---|---|---|---|---|---|---|---|---|
| Bucharest | 14.5% | 12.9% | 9.6% | 9.7% | 8.8% | 8.6% | 7.9% | 6.9% | 10.4% |
| Prague | 1.8% | 5.3% | 14.6% | 22.4% | 18.5% | 14.2% | 10% | 6.3% | 6.3% |

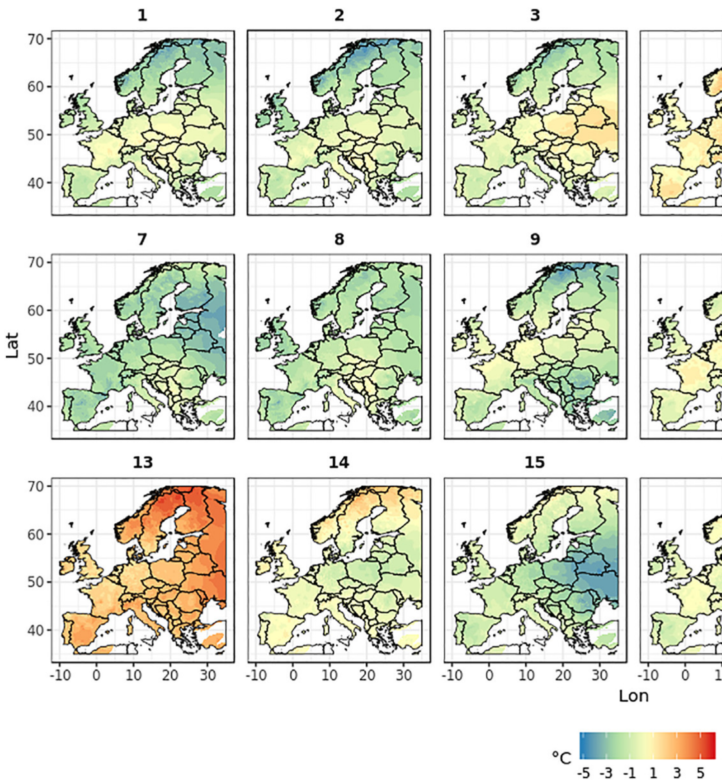


**Fig. 4.** Mean deviation of daily minimum temperatures for all CTs against the multiannual mean.

**Table 4**
Number of cases and relative frequencies of the "extreme" UHI occurrence with the intensity over 4 °C in groups of types.

| Season | (Anti)cyclonic group | all cases | cases with UHI intensity over 4 °C | | | |
|---|---|---|---|---|---|---|
| | | | Prague | | Bucharest | |
| | | | number of cases | percent of all cases | number of cases | percent of all cases |
| Spring | anticyclonic | 1572 | 128 | 8.1 | 199 | 12.7 |
| Spring | cyclonic | 1740 | 113 | 6.5 | 223 | 12.8 |
| Spring | all | 3312 | 241 | 7.3 | 422 | 12.7 |
| Summer | anticyclonic | 2045 | 83 | 4.1 | 223 | 10.9 |
| Summer | cyclonic | 1267 | 52 | 4.1 | 150 | 11.8 |
| Summer | all | 3312 | 135 | 4.1 | 373 | 11.3 |
| Autumn | anticyclonic | 1825 | 111 | 6.1 | 198 | 10.8 |
| Autumn | cyclonic | 1451 | 68 | 4.7 | 124 | 8.5 |
| Autumn | all | 3276 | 179 | 5.5 | 322 | 9.8 |
| Winter | anticyclonic | 1783 | 153 | 8.6 | 152 | 8.5 |
| Winter | cyclonic | 1466 | 122 | 8.3 | 94 | 6.4 |
| Winter | all | 3249 | 275 | 8.5 | 246 | 7.6 |
| Year | anticyclonic | 7235 | 475 | 6.6 | 772 | 10.7 |
| Year | cyclonic | 5924 | 355 | 6.0 | 591 | 10.0 |
| Year | all | 13,159 | 830 | 6.3 | 1363 | 10.4 |

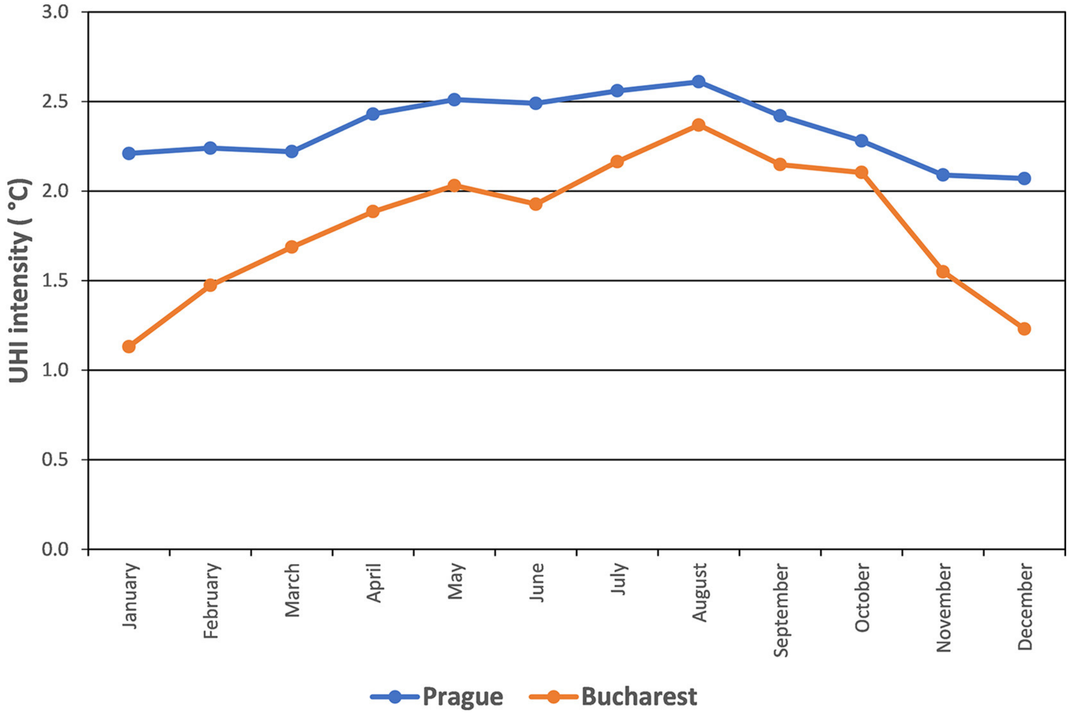


**Fig. 5.** Annual regime of the mean monthly UHI intensity in Bucharest and Prague.

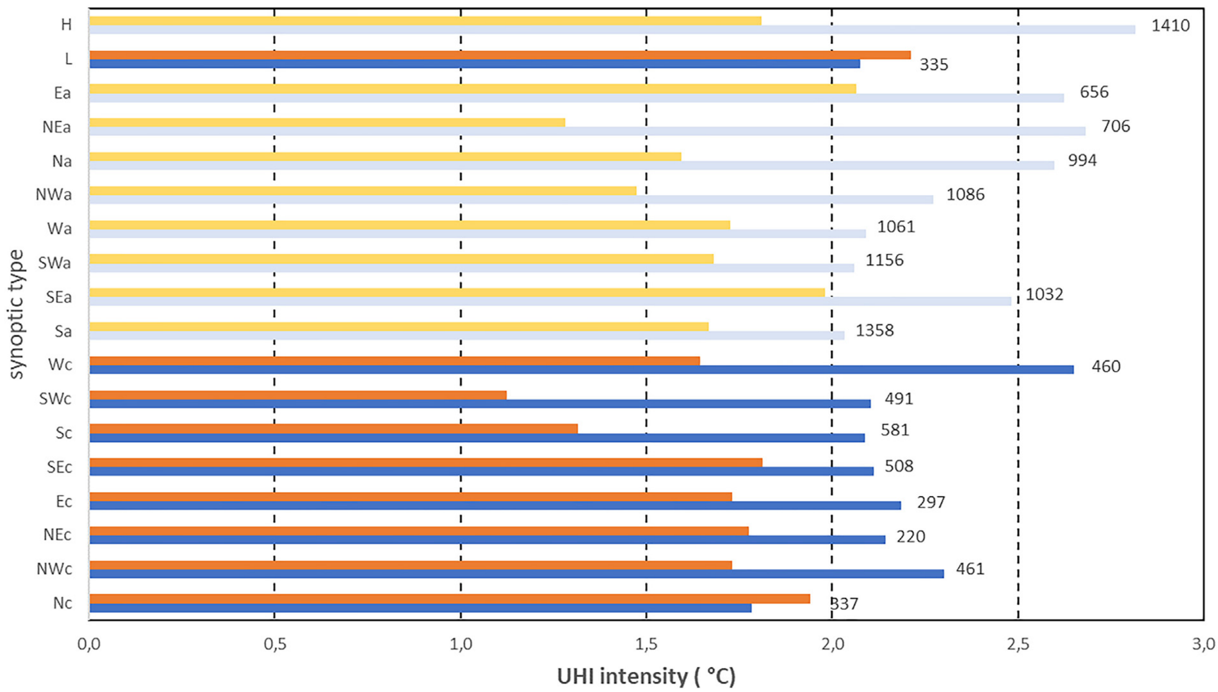


**Fig. 6.** Average annual intensity of the UHI for different circulation types in Prague (blue) and Bucharest (red-orange). Cyclonic circulation types are marked in dark colours, anticyclonic types are marked in light colour, and figures mean the total number of days for each CT. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 5**
Directional groups and corresponding circulation types.

| Directional group | Types |
|---|---|
| NC | Ec, SEc, Sc |
| SC | Nc, NWc, Wc, L |
| NA | Wa, NWa, H |
| SA | SEa, Ea |

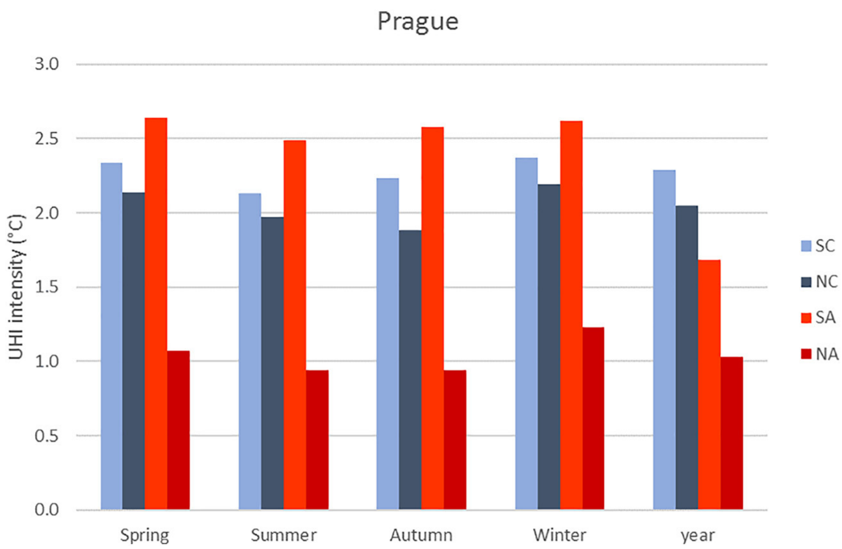


**Fig. 7.** Average seasonal and annual values of the urban heat island intensity in the directional groups for Prague.

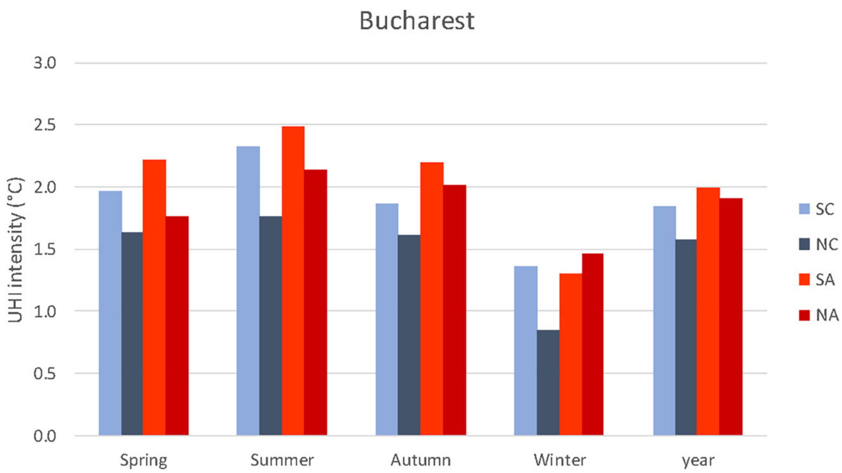


**Fig. 8.** Average seasonal and annual values of the urban heat island intensity by directional groups for Bucharest.

/ 100 years). Explained variance is generally smaller in Prague compared to Bucharest with higher values for winter and spring, while in Bucharest the highest explained variance is in spring and summer. Figs. 9 and 10 show the variability and trend lines at annual scale (left panels), the seasons with highest trend (middle panels), and the highest trend for given group and season (right panels).

## 7. Discussion

The urban heat island is a very important climate feature of both studied cities, Prague and Bucharest, especially under era of climate change leading to larger heat stress during warm and heat periods, and more frequently occurrence of tropical days and length of periods with continuous tropical days. The number of warm and/or tropical nights is expected to increase in the next decades (IPCC, 2013) and the question of UHI mitigation needs to be carefully considered by urban planners and architects.

**Table 6**
Long-term changes in the UHI intensity: linear trend (°C/100 years) and determination coefficient $R^2$ (explained variance). Statistically significant trends are emphasized in bold.

| Group | season | count | Prague | | Bucharest | |
|---|---|---|---|---|---|---|
| | | | trend (°C/100 years) | explained variance | trend (°C/100 years) | explained variance |
| NA | spring | 673 | **1.7** | 0.17 | **3.8** | 0.36 |
| | summer | 1413 | *0.4* | 0.02 | **3.9** | 0.46 |
| | autumn | 759 | *1.2* | 0.11 | **2.6** | 0.18 |
| | winter | 712 | *1.2* | 0.08 | **3.5** | 0.27 |
| | year | 3557 | **1** | 0.14 | **3.4** | 0.54 |
| NC | spring | 501 | *1.2* | 0.1 | **2.9** | 0.16 |
| | summer | 462 | *0.8* | 0.03 | **3.6** | 0.27 |
| | autumn | 214 | *0.9* | 0.04 | *0.2* | 0 |
| | winter | 209 | *1.1* | 0.06 | *2.3* | 0.08 |
| | year | 1386 | *0.9* | 0.1 | **3.2** | 0.42 |
| SA | spring | 363 | **2.1** | 0.17 | **3.8** | 0.32 |
| | summer | 230 | *-2* | 0.03 | **4.6** | 0.3 |
| | autumn | 645 | *0.9* | 0.05 | **2.2** | 0.13 |
| | winter | 450 | **3.4** | 0.26 | **3.1** | 0.11 |
| | year | 1688 | **1.5** | 0.19 | **3** | 0.4 |
| SC | spring | 594 | **2.2** | 0.22 | **4.5** | 0.38 |
| | summer | 238 | *1* | 0.05 | **3.6** | 0.2 |
| | autumn | 357 | ***2.4*** | 0.32 | ***3.5*** | 0.21 |
| | winter | 404 | **2.4** | 0.22 | **2.8** | 0.2 |
| | year | 1593 | **2.1** | 0.36 | **3.3** | 0.43 |
| All | spring | 3312 | **1.5** | 0.21 | **4.2** | 0.53 |
| | summer | 3312 | *0.8* | 0.06 | **4** | 0.5 |
| | autumn | 3276 | **1.1** | 0.12 | **2.1** | 0.22 |
| | winter | 3249 | **1.7** | 0.23 | **2.9** | 0.33 |
| | year | 13,149 | **1.3** | 0.23 | **3.3** | 0.55 |

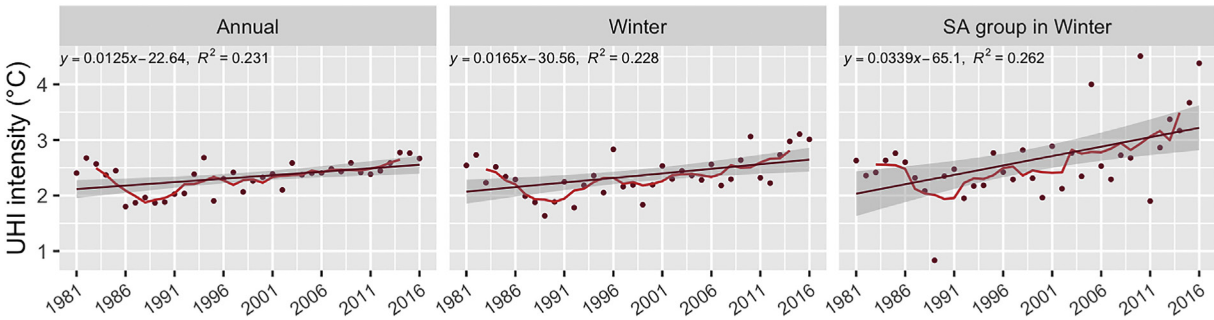


**Fig. 9.** Variability and linear trendline of the UHI average annual intensity for all situations (left), in winter (middle) and SA group in winter (right) for Prague. Regression line and 5 years running mean are interspersed with a graph. The grey shaded area represents the upper and the lower bounds for the confidence interval (set at 95%) from the linear prediction model line.

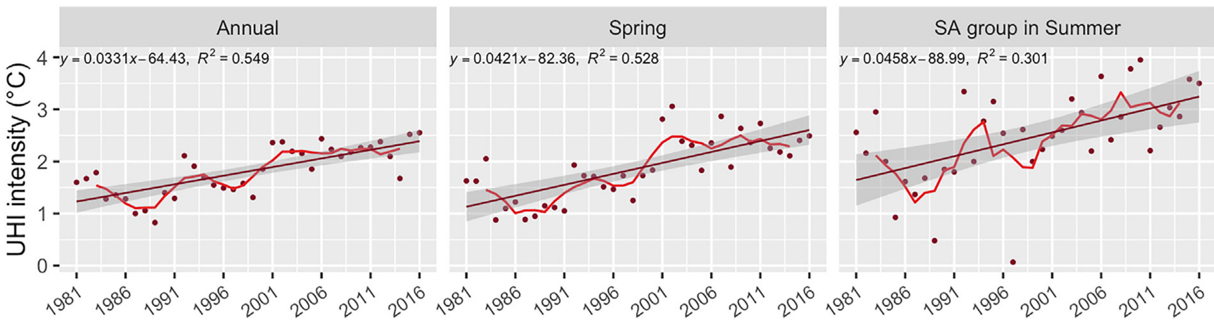


**Fig. 10.** Variability and linear trendline of the UHI average annual intensity for all situations (left), in spring (middle) and SA group in summer (right) for Bucharest. Regression line and 5 years running mean are interspersed with a graph. The grey shaded area represents the upper and the lower bounds for the confidence interval (set at 95%) from the linear prediction model line.

This study focuses on the connection between UHI development and various synoptic scale circulation patterns during period of 1981–2016. Based on the weather classification provided by the COST 733 Action, we delimited 18 circulation types, half of them cyclonic, and half of them anticyclonic. The classification holds objectivity and it is replicable, which is an important reason for using it. It has to be mentioned that the usage of thresholds and criteria partly involves expert-based decisions. The size of the area containing Bucharest and Prague fits the synoptic analysis, but the position of various pressure system centres can lead to different weather conditions in both cities and influence the UHI development.

The local geography and urban characteristics trigger differences in the UHI intensity and behaviour. With lower population, but more extended spatially, Prague's nocturnal UHI is more intense than the Bucharest one in terms of monthly average. The location of the urban stations is also important in the differentiation, since Prague-Klementinum is placed in a compact built-up area, while București-Filaret is situated in an urban park.

City enlargement, traffic increase and conversion of green areas into built up zones have constantly augmented the UHI intensity in both cities during the last decades. The more than doubled increase for Bucharest compared to Prague can be connected to larger changes in the land-use in this city. For Bucharest, one explanation regarding its positive trends in UHI intensity is the aggressive urbanisation that started in late 1970s by the communist regime and has continued during the recent decades. The patterns of increase are quite similar for both cities (see Figs. 9 and 10), which emphasizes that in this respect the role of the general atmospheric circulation is more important than local land cover changes or different geographic conditions (central Europe/ South-Eastern Europe). A thorough analysis shows that an accumulation of more cyclonic and/or abnormal warm situations would lead to lower UHI intensity. These interesting feature can be observed for both cities in the last pentad of the 1980s, also reflected in the annual means of the UHI intensity (Fig. 10). As regards the temporal variability of the UHI, the increasing trends are more often statistically significant for Bucharest (with more continental climate) compared to Prague.

## 8. Conclusions

This study has analysed the influence of synoptic scale atmospheric circulation on the UHI intensity for Prague and Bucharest, as well as temporal variability of UHI. At the best of our knowledge, it is the first comparison between two European cities from this perspective. The comparison shows differences and similarities, as described below, and demonstrated the utility of the European circulation types provided by the COST 733 Action.

The UHI phenomenon is common for both cities, at different intensities. For Prague, the average UHI intensity computed from daily minimum air temperatures is 2.3 °C, while for Bucharest is 1.8 °C. The maximum values of the mean UHI intensity can exceed 4 °C (e.g. in Bucharest it occurs in 10% of all cases). The annual course of monthly mean values of UHI intensities has higher amplitude for Bucharest (1.2 °C) than for Prague (0.6 °C). This difference can be caused by higher anthropogenic heat production in downtown Prague during the winter months caused by higher heating in older buildings with less efficient isolation than in downtown Bucharest triggering the intense UHI development. The highest monthly average of UHI intensity occurs in August for both cities when built areas still accumulate radiant heat during daytime in the summer months (JJA) and releasing it slowly during night, while the rural neighbourhood starts cooling more rapidly during longer nights in August.

Different synoptic circulation types influence the UHI development and intensity in the two cities. The UHI of Prague develops especially under H and NEa types, i.e. south- to southwesterly winds, typically under the influence of anticyclone with warm air advection. For Bucharest, the largest intensity of UHI occurs especially under Ea type, i.e. situation with southerly wind component having more or less anticyclonic circulation. The lowest intensity of UHI is observed under Nc type for Prague and SWc for Bucharest. The statistically significant increasing trend of the UHI intensity has been proved for both cities with much larger trend found for Bucharest (3.3 °C vs. 1.3 °C for Prague per 100 years). The changes in the central parts of the two cities were quite different in the last decades, being more dramatic in Bucharest and less pronounced in Prague. This increase differs at seasonal level. In Prague, larger significant increase can be observed during winter, especially for SA and SC directional group, while for Bucharest the largest increase can be found during spring season (especially for SC directional group) and in summer (mainly for SA group). It can be concluded that for both cities the UHI is more intense under anticyclonic situations with southern winds. Such cases are connected with a weakening of atmospheric pressure horizontal gradient leading to weak winds preventing mixing of air in the city and its surroundings and to greater direct radiation values supporting UHI development.

For Prague, the further increase of the UHI intensity is expected since the density of built up areas is increasing and its metropolitan plan prefers the redevelopment of brown fields, usually meaning new more floors buildings. There are plans in mitigating the UHI effects mostly in microclimate scale like adjustment of street canyons, using of green roofs etc., but these measures are probably not so widespread to exceed the UHI increasing trend in the first half of this century.

Similarly, the urban expansion is an ongoing process in Bucharest, together with population increase, business and transport intensification. At the same time, adaptation and mitigation measures are still isolated and far from being efficient. UHI impact is likely to increase unless the urban development is rapidly shaped according to the real needs.

Both Prague and Bucharest will be at least 1 °C warmer by the middle of the century (Cheval et al., 2017)

Considering the comparative approach adopted for this study, including the application of a common methodology for two cities with distinct geographical settings, the use of this concept can be easily performed in other urban areas of similar sizes and complexity.

## Declaration of Competing Interest

None

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