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# Relationship between weather conditions advantageous for the development of urban heat island and atmospheric macro-circulation changes

**Short title:**
Relationship between urban heat island and macro-circulation changes

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**Abstract**

Urban heat island and climate change belong to two separate scientific fields within meteorology nowadays. Climate change, however, may affect the characteristics of urban heat island as well. Various atmospheric macro-circulation conditions determine the frequency of certain weather conditions at a given area, thus they influence the frequency of the occurrence of conditions advantageous for urban heat island development. In the present research the time series data of conditions advantageous for urban heat island (AMC – Advantageous Meteorological Conditions) was determined in the case of Debrecen (Hungary) and similar patterns existing in the AMC time series were searched in those of NAO (North Atlantic Oscillation), EA (East Atlantic Oscillation), EA/WR (East Atlantic/Western Russia Pattern) and SCA (Scandinavian Oscillation) indices for the period between 1961 and 2010 using Gábor–Morlet wavelet transformations. Several significantly coherent oscillations were found. The occurrence frequency of advantageous meteorological conditions can be approximated from macro-circulation conditions in these periods, according to the concept of heat island. These estimations are consistent with the calculated AMC time series. This proves that there is some relationship between macro-circulation and heat island development. Based on the results, using seasonal and climate models the changes of urban heat islands at seasonal and climatic scales may become predictable.

**Keywords:**
urban heat island, atmospheric macro-circulation, wavelet transformation, Gabor-Morlet wavelet, teleconnections, time-series coherence

# 1 Introduction

Nowadays the number of people living in urban areas is increasing. Since the quality of life is significantly influenced by weather and adaptability to the conditions determined by weather, studying meteorological features in urban environments is increasingly important in an urbanized world (Kinney, 2008). Changes in the climate or the atmospheric macro-circulation may influence the characteristics of heat islands as well (Arnfield, 2003; McCarthy *et al.*, 2010). This means that various macro-circulation conditions increase the occurrence frequency of certain weather events and reduce the occurrence frequency of others. As a result, the fact that frequency changes of conditions advantageous for urban heat island could be associated with changes in macro-circulation conditions could be regarded as hypothesis. Studying these effects of climate change on heat island is increasingly interesting.



## 1.1 Aims

The primary aim of this study is to find the basics of a method which could be useful to predict or estimate the changes of the characteristics of urban heat island at a climatic time scale. This would be based on seasonal or climate model outputs and similar patterns in the AMC and the macro-circulation time series would be detected. Therefore we focus on similar patterns between a few indices (NAO – North Atlantic Oscillation; EA – East Atlantic oscillation; SCA – SCAndinavian oscillation; EA/WR – East Atlantic/Western Russian oscillation) describing the oscillation of macro-circulation features influencing weather in the Carpathian Basin and the time series of the occurrence frequency of conditions advantageous for urban heat island development (AMC – Advantageous Meteorological Conditions) calculated for Debrecen (Hungary).

The secondary aim of this paper is to verify that wavelet transformation is an appropriate basis for the statistical model with which AMC changes could be predicted by analyzing the predicted time series of the macro-circulation indices of climate models. In time periods when coherency between the time series of AMC and macro-circulation indices is strong, the frequently occurring macro-synoptic settings and the weather of the Carpathian Basin can be predicted on the basis of macro-circulation conditions. The occurrence frequency of urban heat island can be estimated on the basis of the conceptual model of heat islands.

## 1.2 Qualitative theoretical bases

Favorable conditions for urban heat island formation are windless nights with clear skies or clear daytime weather, and the development of urban heat island is also influenced by recent precipitation (Morris *et al.*, 2001). Minor and slow changes (in climatic or seasonal time scale) in meteorological elements are probably the regional effects of climate change. As a result, it can be presumed that the frequency of advantageous meteorological conditions for urban heat island is determined by climate change (Molenaar *et al.*, 2016; Sachindra *et al.*, 2016).

Recent studies revealed that the morphological properties of the city as well as the difference between the urban and rural boundary layer height may affect the urban heat island development (Theeuwes *et al.*, 2017). Since the morphology of Debrecen is given morphology aspects were ignored.

Several decades long oscillations can be found among those of atmospheric macro-circulation systems, like the AMO (Atlantic Multi-Decadal Oscillation) phenomenon (Dima and Lohmann, 2007). They influence the length and frequency of various macro-circulation conditions, therefore it is worth studying whether changes in the macro-circulation can be detected in the time series of the frequency of climatic conditions advantageous for urban heat islands.

The macro-scale circulation systems in the temperate climate zones are directed by action centres. These are low or high pressure atmospheric formations present permanently or periodically, the only permanent is the Antarctic one. Their actual state is in close connection with the wave features of the polar front, the behavior of the Rossby waves and can determine fundamentally the weather conditions over large areas and long periods. Their state can be described by atmospheric macro-circulation indices that are anomalies of the pressure differences of certain selected action centres.

Weather of Europe and the Carpathian Basin is influenced by several such action centres. Permanent action centres include the Azores High and the Icelandic Low. In winter, the Siberian High, while in summer, the Iranian Low occur due to thermal reasons. In order to describe the pressure difference between the Azores High and Icelandic Low, the NAO (North Atlantic Oscillation) index can be applied, the positive anomaly of which suggest the strongly developed state of the two pressure systems. At such times zonal flow is strong above the Atlantic Ocean and Europe.

Negative AO (Arctic Oscillation) phase especially in winter suggests strong Siberian High and weak Icelandic Low. At such times blocking conditions occur frequently when meridional flow prevail instead of zonal one, and variably strong anticyclone develops at locations different from the usual action centres and for shorter time periods (generally for less than one month). In such conditions dry and very cold winter or very hot summer occurs in Central and Eastern Europe. Location of the blocking anticyclones is not random (Barriopedro *et al.*, 2006), they appear often above Great Britain and Scandinavia or above Central Europe in summer and the East European Plain in winter. Macro-circulation indices describing blocking anticyclones – similar to those describing the permanent and semi-permanent action centres – exist, for example EA (East Atlantic Oscillation) and SCA (Scandinavian Oscillation). The main variability with greatest amplitude in the time series of EA and SCA are at the time scale of a few days or weeks which is the time scale of blocking. However, oscillations with several months and years can also be identified.

# 2 Methods

## 2.1 Calculation of conditions advantageous for urban heat island development

Urban Heat Island Intensity (UHI) is defined as the daily maximum of hourly differences between air temperatures measured at a height of 2 m in the city and at a rural site. Three important factors (precipitation, wind speed, cloudiness) were considered when the conditions for urban heat island formation were defined (Kim and Baik, 2005). These factors were associated with threshold values (*Ta-*

*ble 1*). According to László *et al.* (2016), four categories can be identified based on the number of conditions met: 0, 1, 2, and 3 standing for disadvantageous, moderately disadvantageous, moderately advantageous and advantageous categories respectively. The relative frequency of days within a year yielding favorable conditions (category 3, when all three conditions met) for heat island development was determined for each year. This time series constitute AMC data.

Definition of the threshold values in *Table 1* was based on the empirical results of studying the relationship between daily maximum UHI intensity measured on a local scale and weather factors (see Bottyán *et al.*, 2005; Landsberg, 1981; László *et al.*, 2016; Oke, 2002; Szegedi and Kircsi, 2003).

## 2.2 Relationship between AMC and variability of climate

Urban environments are exposed to natural climate variability and the oscillations of atmospheric processes. Such oscillations occur seasonally within a longer time period the effects of which on temperature and precipitation can be estimated relatively well for regions of the Earth. Climate change in a given region may influence temperature and precipitation in other, more distant areas as well. This is caused by teleconnections. During the process energy from the climatically variable source region is transported towards distant areas by the atmosphere. In this way, natural climatic variability influences significantly the occurrence of extreme temperature and precipitation events at a given location and time (Hurrell and Deser, 2010).

Variability of atmospheric circulation is considered to be one of the most important factors the annual or decadal periods of which determine factors controlling meteorologically the urban heat islands, namely precipitation, wind speed and cloudiness (Wilby *et al.*, 1997). Relationship between calculated advantageous conditions (AMC) and macro-circulation variability can be assumed, therefore indices representing the atmospheric circulation system were applied in the study including NAO, EA, SCA and EA/WR. Time series were obtained from the NOAA website (`http://cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml`).

## 2.3 Description of the macrocirculation indices

### *2.3.1 North Atlantic Oscillation*

North Atlantic Oscillation is one of the most significant climatic phenomena determining weather in the northern hemisphere in the Atlantic region over most of the year. NAO index gives the oscillation of the pressure difference between the Icelandic Low and the Azores High and also represents the strength of zonal winds along northern mid-latitudes (Hurrell *et al.*, 2001). In its strong positive phase westerly winds carry warmer and cooler, wetter air into Europe in winter and summer respectively. It may also cause the development of cyclone bombs in extreme cases (Sanders and Gyakum, 1980). Strong Icelandic cyclone activity results in wet weather in Northern and Central Europe while in the lack of this cyclone activity continental air flows towards the Mediterranean region from Eastern Europe taking drier air with itself.

### 2.3.2 *East Atlantic Oscillation*

East Atlantic Oscillation can be defined very similarly to NAO with pressure centres located to the west of the British Isles and near the shores of Iberia and North Africa. It represents subtropical connections of the changes in the temperate zonal winds. In its positive phase weather warmer than average is expected for entire Europe with wet weather in the north and in Scandinavia and dry weather in Southern Europe (Barnston and Livezey, 1987). According to more recent research, it determines the usual weather together with NAO in spite of that several decades long oscillation of this index has greatest amplitude in the data series (Nesterov, 2010).



### 2.3.3 *Scandinavian Oscillation*

Primary circulation centres of the Scandinavian Oscillation are located above the Scandinavian region while secondary centres are located above Western Europe and Eastern Russia. In the case of positive anomaly anticyclonic blocking situations appear above Scandinavia and Western Russia resulting in more meridional flow in place of zonal flow. At such conditions temperatures are lower than average in Scandinavia. In Central Russia, Western, Central and Southern Europe, more precipitation can be observed than the average while in Scandinavia the weather becomes drier.

### 2.3.4 *East-Atlantic/Western-Russian Oscillation*

Centres of the East-Atlantic/Western-Russian Oscillation are located in the North Atlantic–Western European, Caspian–Western Russian and Northeastern Chinese regions. In the case of its positive phase, precipitation is less than average in Central Europe but more than average in Eastern China. At the same time temperatures are higher than average in Eastern Asia and lower in Western Russia and Northeastern Africa (Ionita, 2014).

## 2.4 Mathematical background

In time-frequency space, Fourier-transformation converts a time series into a frequency spectrum which loses the time dependent informations. The result of the wavelet transformation contains both time and frequency dependent informations. In this way it is useful to detect temporal variability of the amplitude of different frequency oscillations in a time series. Cross wavelet transformation can highlight time dependence of coherence between the two time series at different frequencies. In essence, this method can be applied to study nonlinear processes, e.g. nonlinear changes in a time series, or nonlinear connections between them. The greatest benefit of the wavelet analysis is that the most changes types (for example permanent and quasi-permanent oscillations, abrupt changes) in a time series can be identified at once. Moreover, statistical connections between changes in two time series can be identified using cross wavelet transformation. In the latter case, other methods (e.g. cross-correlation analysis) are applicable only with certain restrictions and careful interpretation of the results is needed: for example, nonlinear correlation analysis methods can be useful, however, the distribution for determining significance cannot be constructed always analytically.

Heisenberg's uncertainty principle applies to the time-frequency space. The phase cell volume is minimal in the case of Gábor-wavelet. This says that the best resolution of the results in the time-frequency space can be earned using Gábor-wavelet as the core function of the wavelet transformation.

The application of wavelet transformation became widespread in time series analyses. The idea of Gábor (1946) was to use mathematical formulation of quantum mechanics in electro-technical signal processing. The theory was completed by Goupillaud *et al.* (1984) who proved the minimal phase cell property of the Gábor-wavelet. Clearing of the steps of practical application of wavelet analysis was done by Torrence and Compo (1998) taking sample time series from climatology and working out statistical tests to study the significance of separating the obtained signs from red and white noise. According to Grinsted *et al.* (2004), this method can be applied in meteorology for example to detect coherent structures (teleconnections) analysing variability of different meteorological characteristics of different areas caused by climate change. Examples of this application are the works by Duffy (2004); Farge (1992); Lau and Weng (1995); Meneveau (1991); Meyers *et al.* (1993); Pal (2014); Pal *et al.* (2016).

Processing of our data was performed using wavelet transformations with one (CWT – Continuous Wavelet Transform) and two (XWT – Cross Wavelet Transform) variables with Gábor–Morlet base (Gábor, 1946; Morlet, 1983). The results of the CWT is shown in *Fig. 1* and those of XWT in *Fig. 2*. The open source MATLAB code from Grinsted *et al.* (2004) was applied to produce the figures.

# 3 Results

## 3.1 Analysis of teleconnections

### *3.1.1 North Atlantic Oscillation*

In the time series of the NAO index, three signs can be identified as significant (*Fig. 1*, NAO). A significant variability with 2 to 3 yr periodicity can be detected between 2008 and 2012. This includes the negative phases of 2008, 2010 and 2012. Blocking situations were more frequent in these three years.



A 8 to 10 year periodicity is present from the 1980s which is significantly strong from 1987 to 1994. The increasing relative frequency of positive phases during this period is recognizable as well as the disappearance of negative phases is evident in the early 1990s and their reappearance after 1994.

Shortly after the appearance of the previous variability, an 11 to 12 yr oscillation began to strengthen. This became significant after 1997 and remained so until 2012. This variability cannot be analyzed precisely because of the cone effect as significance values can be distorted, i.e. enhanced artificially. A later study is necessary to determine whether this periodicity remains permanent or not.

There is a cca. 4 yr periodicity at around 1985 to 1987. It is not significant but it is important as it contributes to a significant signal in the AMC-NAO cross wavelet spectrum. This relates to a smaller but notable abrupt change in the NAO time series as a strong minimum occurred after a 2 yr positive dominance after which the frequency of main oscillation increased. These NAO anomalies are because of the macro-circulation which caused frequent windy weather in that period and the very cold winters of 1985 and 1987 in the Carpathian Basin. This sign will emerge later also in the time series of other indices.

#### 3.1.2 East Atlantic Oscillation

Two significant signs were found in the time series of the East Atlantic Oscillation (*Fig. 1*, EA). First is a clear rise from 1950 to now. This is directed by step-like increases of the average instead of a significant linear trend. Abrupt changes can be identified, for example at 1977 when the negative dominance faded away and positive and negative phases appear alternately, or at 2012 when negative phases disappeared. Changes of periods greater than 6 to 7 yr are missing in the studied period.

The second sign is a 4 to 6 yr periodicity dominant between 1965 and 1980. In that period, longer negative phases were interrupted with slightly positive ones in every two years and every second negative phase (around 1967, 1972 and 1976) was stronger than the others.

Later in this period, a 2 yr oscillation also appears which is significant around 1975. That was the first strong positive phase and actually the strongest ever until 1998.

These signs disappear by 1980, then reappear around 1985 (although not significantly) which means that the 4 yr periodicity is present at 1985 in this index, too. In this case, a strong minimum is in 1984 after which the positive phases were weaker than before until late 1987.

### *3.1.3 Scandinavian Oscillation*

Significant nonlinear changes were also found in the time series of Scandinavian Oscillation (*Fig. 1*, SCA). Stronger positive phases dominated until 1980. These changes are mainly shorter variabilities, but enhanced power spectrum densities are visible also at longer periods.

2 to 3 yr periodicity is identifiable from 1968 to 1972 which then shifted to a longer time period. This stronger sign then remains significant until 1977 with a 3 to 5 yr period. Short negative phases interrupted the positive dominance of the anomaly index.

A 2 to 5 yr variability appears with significantly enhanced power spectrum density from 1998 to 2000. In this case, negative dominance emerged, then faded away.

Of the longer period variabilities, a 13 to 15 yr periodicity is more enhanced from the 1980s, although not significant. While it is not significant in the range inside of the cone, it remains identifiable outside as well. If the variability remains present in the next decade of years, the power spectrum density can increase further.



### *3.1.4 East-Atlantic/Western-Russian Oscillation*

There are two significant changes in the time series of the EA/WR index (*Fig. 1*, EA/WR). In one hand, a 4 to 6 yr periodicity appears in the late 1960s but it is mainly out of cone. It is not visible by the naked eye in the time series data because it is hidden by shorter changes of greater amplitudes.

Another is 2 to 4 yr variability present from 1980 to 1985. Two strong minimums are observable in late 1981 and early 1984.

A 8 to 10 yr periodicity sign until 1985 is not significant but notable. The relative frequency and strength of negative phases are increased around 1950, 1960, 1970 and 1980.

#### *3.1.5 Advantageous meteorological conditions for heat island*

Time series of meteorological conditions advantageous for heat island development (AMC) were also analyzed using CWT. One significant variability identified is a 4 yr change around 1985 where AMC decreased as the 1985 to 1987 yr period had often windy weather.

Another significant sign is identified from 1997 to 2004 with 2 to 3 yr periodicity. In this period, the relative frequencies of zonal and meridional macro-circulation situations changed at several times. For example 1999 has mainly meridional situations but 2000 and 2001 have mainly zonal flows and then meridional flows became more frequent from the winter of 2001/2002.

Noticeable signs are a 4 to 6 yr periodicity around 1970 and an 8 to 10 yr variability from 1970 to 1995. Although they are not significant, they are contributions to some significant signs in the cross-spectra discussed in the following subsection.



### 3.2 Results of cross wavelet analysis

#### *3.2.1 North Atlantic Oscillation*

Using cross wavelet transformation of AMC and NAO time series, there can be hardly any significant coherences identified (*Fig. 2*, AMC-NAO). The only one is a 4 yr common variability from 1980 to 1987 which is barely significantly strong in 1985. The changes are in-phase. It indicates that in that period, changes of the

Icelandic Low and Azores High directly affected the weather in the Carpathians so that the advantageous meteorological conditions changed simultaneously. It is worth remembering that a notable, but not significant increase was found in the NAO CWT spectrum as mentioned in *Section 3.1.1*. Its role is that a cross-spectrum can be significantly strong in a place where the two separate CWTs are not significant.

The second notable sign is an 8 to 10 yr periodicity with about 45° phase shift, AMC changes follow NAO changes. This phase shift means a circa 1 yr difference.

### *3.2.2 East Atlantic Oscillation*

A coherent pattern in the AMC-EA cross-spectrum (*Fig. 2*, AMC-EA) can be detected from 1967 to 1975 with a periodicity of 4 to 6 yr. This is the case when EA has a dominating variability with the same periodicity. In AMC time series, this pattern can also identified although it is not significant. Its phase indicates a somewhat less than 1 yr delay of AMC to EA.

Another significant sign is a 3 to 6 yr oscillation around 1985. The CWT of both the AMC and EA time series show increased power spectrum density at this time and frequency range. Due to the similar definitions of the EA and NAO indices, their time series can be correlated. Therefore it can be assumed that the same macro-scale effects caused both the AMC-NAO and the AMC-EA coherences. Physically, it can be related to the abrupt changes occurring in the time series at around 1985 which can be related to the very cold winter periods of 1985 and 1987, and the unusually windier weather in that period in the Carpathian basin. The phase shift indicates that the decreasing of AMC precedes that of EA. NAO decreasing, as it is synchronous with the AMC decrease, also precedes the EA decrease. This means that when the Icelandic cyclone activity becomes weaker, the relative frequency of British blocking situations begin to increase. At the beginning of this period, northwesterly flow regimes dominated the weather of Central Europe (sometimes called as half-blocking situations) in which the average wind is the strongest.

#### *3.2.3 Scandinavian Oscillation*

In the case of AMC-SCA cross wavelet spectrum (*Fig. 2*, AMC-SCA), four different significantly coherent variabilities can be detected. The first two are a 2 yr variability before 1970 and a 4 yr one after 1970. These match to the significant 2 to 5 yr variability of SCA from 1968 to 1977, but AMC wavelet spectrum density is only increased in this two ranges. The phase shift indicates SCA changes with about a quarter period later than AMC changes.

Next significant sign is a 3 to 4 yr periodicity from 1980 to 1985. A sign found in the SCA spectrum near this range is not significant and changes of AMC precede those of SCA. Thus, existence of any relation of this sign with the mentioned events of 1985 to 1987 is less likely.

Lastly, an around 3 yr variability is found from 1995 to 2000. The changes are in-phase, but AMC changes get significant after 2000, when SCA changes fade. In this period, changes of relative occurrence frequency of Scandinavian blocking anticyclones might affect directly the occurrence frequency of the advantageous meteorological conditions. In the Scandinavian blocking macro-circulation situations, however, the Carpathian basin can have anticyclonic and cyclonic weather depending on the strength and the spatial coverage of the anticyclone: the Mediterranean cyclones can go over the Carpathian basin or may remain further to the south.

#### *3.2.4 East-Atlantic/Western-Russian Oscillation*

The AMC-EA/WR cross wavelet spectrum indicates three significant coherence patterns exactly matching with increased AMC variability patterns. The first two are present also in the EA/WR time series.

A 4 to 6 yr periodicity is identifiable from 1965 to 1970. The phase shift changes with the time period indicating a 3 yr delay of AMC to EA/WR independently of the time period.

A 3 to 4 yr periodicity is significant from 1980 to 1987. In the later part of this range, EA/WR variability fades. The phase shift indicates the opposite direction of changes.

The third sign found is a 2 to 3 yr coherence from 1997 to 2003 which is an in-phase common variability. This is identifiable as significant in the AMC series, but the power spectrum density in the wavelet transform of AMC time series is not high.



### 3.3 Discussion

The above results are the signs of possible common variabilities of the macro-circulation indices and the frequency of the meteorological conditions advantageous for urban heat island development. To prove the connections, explanation of these with real meteorological events is needed. Some explanations were made in the previous subsections at some of the changes found in a qualitative manner. „Naked eye" analysis of the 3 month running averaged index datasets (Barnston and Livezey, 1987) were made in order to identify (when possible) the signs with apparent changes in the time series. More detailed analysis of the real weather and its relation with the macro-circulation indices and the advantageous conditions for heat island development may be helpful to identify the physical connections between the phenomena. In this section we summarize the signals found, and explain them with the real meteorological processes and their influence on urban heat island.

Significantly high power spectrum density in the CWT of NAO and moderate in the XWT of it with AMC indicates that the changes of the occurrence frequency of weather conditions advantageous for urban heat island development show some similar patterns, meaning that the urban heat island development can follow NAO index changes. The 45° phase shift indicates that the changes in the advantageous meteorological conditions follow changes in NAO by 1 year. In the AMC dataset, a significant 4 yr periodicity is visible at around 1985. A slight increase in NAO dataset can also be detected which makes a significant increase in the XWT of NAO. The changes are in phase meaning that in the mid 1980s, the NAO and the AMC follow each other tightly. In the Carpathian Basin, the 1985 and 1987 winters produce extreme cold weather with frequent snow storms which are more frequent at low NAO, resulting in that urban heat island development is less possible because of the wind and cloudiness. When Scandinavian oscillation rises, anticyclonic influence increases in the Carpathian Basin. In such periods, conditions advantageous for urban heat island development becomes more frequent, thus the XWT of SCA against AMC also rises significantly. These were found with 2 to 4 yr periods. The EA/WR dataset shows a significant variability with 2 to 4 yr period in the early 1980s which doesn't coincide with the 4 yr periodicity in the AMC later. A smaller increase in EA/WR is found after 2000 with 2 to 4 yr periodicity. The significant increase in AMC there makes a significant signal in XWT. The pattern in the EA/WR index resulted in the greater precipitations in 1999 and the dry weather in 2001. In accordance with this, AMC frequency also rises in this period.

The above results prove that the variability of atmospheric circulation determines the distribution of precipitation and temperature in both time and space. It also determines the pattern of climatic elements, so it has influences on changes of conditions advantageous for heat islands in time in the studied time periods. As a result of the cross wavelet transformation, significant common periods were detected between the oscillation indices of macro-circulation and the frequency time series of AMC. Therefore teleconnections between these macro-circulation processes and urban heat island can be identified. Presented results support that wavelet analysis is a useful tool in time series analysis. Apart from these, common periodicities and phase connections were exposed by comparing time series using cross wavelet transformation. This result proves that non-linear changes of conditions advantageous for urban heat island could be influenced significantly by certain changes of large-scale atmospheric circulations.



## 4 Conclusions

Dynamics of large-scale atmospheric circulation determines fundamentally types of flow (zonal, meridional) thus also temperature and precipitation anomalies. The changes in macro-circulation over longer periods of time are determined by pressure difference anomalies between low and high pressure centres, the measurement values of which are macro-circulation oscillation indices. Among them, oscillation indices having greatest influence on the weather of the Carpathian Basin were selected (NAO, EA, EA/WR, SCA). Significant common variability between these indices and the frequency time series of weather conditions advantageous for urban heat island development was detected. North Atlantic and East Atlantic Oscillations represent the strength of zonal winds that influences meteorological parameters controlling urban heat island development. In the case of more marked zonal flow, advantageous conditions occur less frequently and temperatures are lower while precipitation is greater than the average around Debrecen. EA/WR and SCA represent meridional flow and more frequent occurrence of blocking conditions when mostly anticyclone dominates in Northern Europe. In such weather situations the occurrence frequency of conditions for urban heat island development is significantly high. Furthermore, in the identified periods – showing significantly similar variability – temperature anomaly is positive while the amount of precipitation is significantly smaller than in the average years. This is proved by the XWT of EA in which we can identify the 4 to 5 yr periodicity after 1985 when EA were in negative phase suggesting cyclonic weather in the Carpathian Basin. The decrease of EA index follows that of AMC frequency which is shown by the ca. 270° phase shift.

Applying wavelet transformation on the time series of AMC and macro-circulation oscillation indices enable the detection of links between them. The analysis of the regional weather in the Carpathian Basin was not needed, it may be only an extra control over the theory. The results of this study show that for predicting changes in the characteristics of urban heat islands, the use of seasonal and climate models able to simulate the changes in macro-circulation is sufficient. Using wavelet transform to the model's output may show coherence patterns similar to those presented here. In such cases, the characteristics of the urban heat island may expected to be similar as well. In this way, urban heat island features become predictable by passing the prediction of regional changes which would lead to an increase of uncertainties. Therefore we hypothesize that this method can decrease the uncertainties in the prediction of changes of urban heat island characteristics.

Further studies of past conditions in other cities are needed to increase the experience with finding more links between urban heat island and macro-circulation. As a next step, some cataloging of the found links would be required to organize their occurrence time period, the places where the link can be found, the macro-circulation indices that link with the AMC time series, the state of, and the changes in, the macro-circulation and in the urban heat island characteristics or other features. In this way, merging common features together, a database can be made that may ease the determination of changes in urban heat island characteristics when coherence patterns from climate models are calculated.




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# References

Arnfield AJ. 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.* **23:** 1–26. doi:10.1002/joc.859.

Barnston AB, Livezey RE. 1987. Classification, Seasonality and Persistence of Low-Frequency Atmospheric Circulation Patterns. *Mon. Wea. Rev.* **115:** 1083–1126. doi:10.1175/1520-0493(1987)115<1083:CSAPOL>2.0.CO;2.

Barriopedro D, García-Herrera R, Lupo AR, Hernández E. 2006. A Climatology of Northern Hemisphere Blocking. *J. Climate* **19:** 1042–1063. doi:10.1175/JCLI3678.1.

Bottyán Zs, Kircsi A, Szegedi S, Unger J. 2005. The relationship between built-up areas and the spatial development of the mean maximum urban heat island in Debrecen, Hungary. *Int. J. Climatol.* **25:** 405–418. doi:10.1002/joc.1138.

Dima M, Lohmann G. 2007. A Hemispheric Mechanism for the Atlantic Multidecadal Oscillation. *J. Climate* **20:** 2706–2719. doi:10.1175/JCLI4174.1.

Duffy DG. 2004. The Application of Hilbert–Huang Transforms to Meteorological Datasets. *J. Atmos. Ocean. Technol.* **21:** 599–611. doi:10.1175/1520-0426(2004)021<0599:TAOHTT>2.0.CO;2.

Farge M. 1992. Wavelet Transforms and their Applications to Turbulence. *Ann. Rev. Fluid Mech.* **24:** 395–458. doi:10.1146/annurev.fl.24.010192.002143.

Goupillaud P, Grossmann A, Morlet J. 1984. Cycle-octave and related transforms in seismic signal analysis. *Geoexploration* **23:** 85–102. doi:10.1016/0016-7142(84)90025-5.

Grinsted A, Moore JC, Jevrejeva S. 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlin. Proc. Geophys.* **11:** 561–566.

Gábor D. 1946. Theory of Communication. *J. IEEE Radio Comm. Eng.* **93:** 429–441. doi:10.1049/ji-3-2.1946.0074.

Hurrell JW, Deser C. 2010. North Atlantic climate variability: The role of the North Atlantic Oscillation. *J. Marine Sys.* **79:** 231–244. doi:10.1016/j.jmarsys.2009.11.002.

Hurrell JW, Kushnir Y, Visbeck M. 2001. The North Atlantic Oscillation. *Science* **291:** 603–605. doi:10.1126/science.1058761.

Ionita M. 2014. The Impact of the East Atlantic/Western Russia Pattern on the Hydroclimatology of Europe from Mid-Winter to Late Spring. *Climate* **2:** 296–309. doi:10.3390/cli2040296.

Kim YH, Baik JJ. 2005. Spatial and Temporal Structure of the Urban Heat Island in Seoul. *J. Appl. Meteorol.* **44:** 591–605. doi:10.1175/JAM2226.1.

Kinney PL. 2008. Climate Change, Air Quality, and Human Health. *Am. J. Preventive Medicine* **35:** 459–467. doi:10.1016/j.amepre.2008.08.025.

Landsberg HE. 1981. *The Urban Climate.* International Geophysics Series **28**. Academic Press, New York; London; Toronto; Sydney; San Francisco.

Lau WKM, Weng H. 1995. Climate Signal Detection Using Wavelet Transform: How to Make a Time Series Sing. *Bull. Am. Meteorol. Soc.* **76:** 2391–2402. doi:10.1175/1520-0477(1995)076<2391:CSDUWT>2.0.CO;2.

László E, Bottyán Zs, Szegedi S. 2016. Long-term changes of meteorological conditions of urban heat island development in the region of Debrecen, Hungary. *Theor. Appl. Climatol.* **124:** 365–373. doi:10.1007/s00704-015-1427-9.

McCarthy MP, Best MJ, Betts RA. 2010. Climate change in cities due to global warming and urban effects. *Geophys. Res. Lett.* **37:**. doi:10.1029/2010GL042845.

Meneveau C. 1991. Analysis of turbulence in the orthonormal wavelet representation. *J. Fluid Mech.* **232:** 469–520. doi:10.1017/S0022112091003786.

Meyers SD, Kelly BG, O'Brian JJ. 1993. An Introduction to Wavelet Analysis in Oceanography and Meteorology: With Application to the Dispersion of Yanai Waves. *Mon. Wea. Rev.* **121:** 2858–2866. doi:10.1175/1520-0493(1993)121<2858:AITWAI>2.0.CO;2.

Molenaar RE, Heusingveld BG, Steeneveld GJ. 2016. Projection of rural and urban human thermal comfort in The Netherlands for 2050. *Int. J. Climatol.* **36:** 1708–1723. doi:10.1002/joc.4453.

Morlet J. 1983. Sampling Theory and Wave Propagation. in *Issues in Acoustic Signal and Image Processing and Recognition*, edited by C.H. Chen, no. 1 in NATO ASI Series, pp. 233–261. Springer, Berlin; Heidelberg.

Morris CJG, Simmonds I, Plummer N. 2001. Quantification of the Influences of Wind and Cloud on the Nocturnal Urban Heat Island of a Large City. *J. Appl. Meteorol.* **40:** 169–182. doi:10.1175/1520-0450(2001)040<0169:QOTIOW>2.0.CO;2.

Nesterov ES. 2010. East Atlantic oscillation of the atmospheric circulation. *Meteorol. Gidrol.* **34:** 794–800. doi:10.3103/S1068373909120048.

Oke TR. 2002. *Boundary Layer Climates*. Routledge, London; New York.

Pal S. 2014. Monitoring Depth of Shallow Atmospheric Boundary Layer to Complement LiDAR Measurements Affected by Partial Overlap. *Remote Sensing* **6:** 8468–8493. doi:10.3390/rs6098468.

Pal S, De Wekker SJF, Emmitt GD. 2016. Investigation of the Spatial Variability of the Convective Boundary Layer Heights over an Isolated Mountain: Cases from the MATERHORN-2012 Experiment. **55:** 1927–1952. doi: 10.1175/JAMC-D-15-0277.1.

Sachindra DA, Ng AWM, Muthukumaran S, Perera BJC. 2016. Impact of climate change on urban heat island effect and extreme temperatures: a case-study. *Quart. J. Roy. Meteorol. Soc.* **142:** 172–186. doi:10.1002/qj.2642.

Sanders F, Gyakum JR. 1980. Synoptic-Dynamic Climatology of the “Bomb”. *Mon. Wea. Rev.* **108:** 1589–1606. doi:10.1175/1520-0493(1980)108<1589:SDCOT>2.0.CO;2.

Szegedi S, Kircsi A. 2003. The effects of the synoptic conditions on development of the urban heat island in Debrecen, Hungary. *Acta Climatol. Chorol.* **36–37:** 111–120.

Theeuwes NE, Steeneveld GJ, Ronda RJ, Holtslag AAM. 2017. A diagnostic equation for the daily maximum urban heat island effect for cities in northwestern Europe. *Int. J. Climatol.* **37:** 443–454. doi:10.1002/joc.4717.

Torrence C, Compo GP. 1998. A Practical Guide to Wavelet Analysis. *Bull. Am. Meteorol. Soc.* **79:** 61–78. doi:10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2.

Wilby RL, O’Hare G, Barnsley N. 1997. The North Atlantic Oscillation and British Isles climate variability, 1865 to 1996. *Weather* **52:** 266–276. doi: 10.1002/j.1477-8696.1997.tb06323.x.

***Table 1:*** *Criteria for conditions advantageous for urban heat island development. Listed elements cannot exceed the value associated with them over the given day. The time series associates the given years with the ratio of days in the suitable category to the total number of days in the year.*

| Meteorological element | Threshold value |
|---|---|
| Daily precipitation | 2 mm |
| Highest wind velocity | $3\,\frac{\mathrm{m}}{\mathrm{s}}$ |
| Highest cloud cover | 5 oktas |

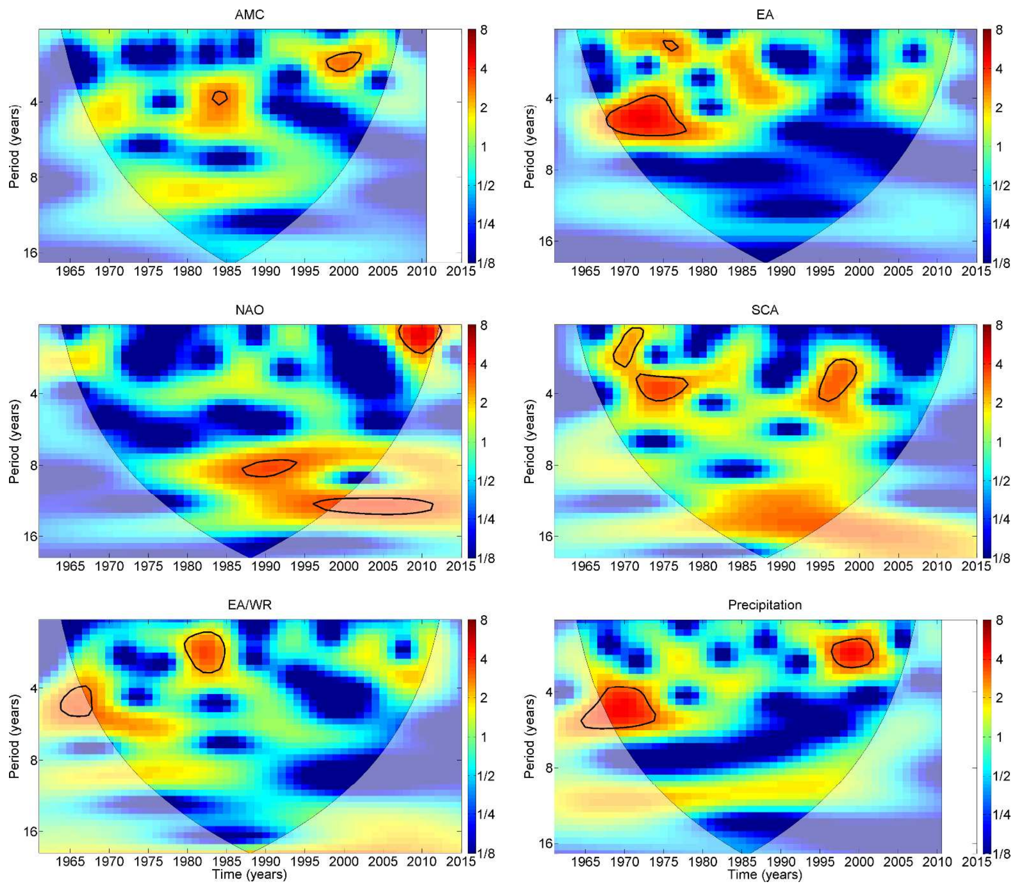


Figure 1: Results of the continuous wavelet transform. Shades denote the dimensionless CWT power spectrum density. High values of it in a some time interval (x axis) with some periodicity (y axis) show that the amplitude of a signal with that periodicity emerges from noise in those years. Black contour denotes the 5% significance level against red noise. The area where edge effect influence distorts the picture is shown in lighter shades.

1184x1032mm (72 x 72 DPI)

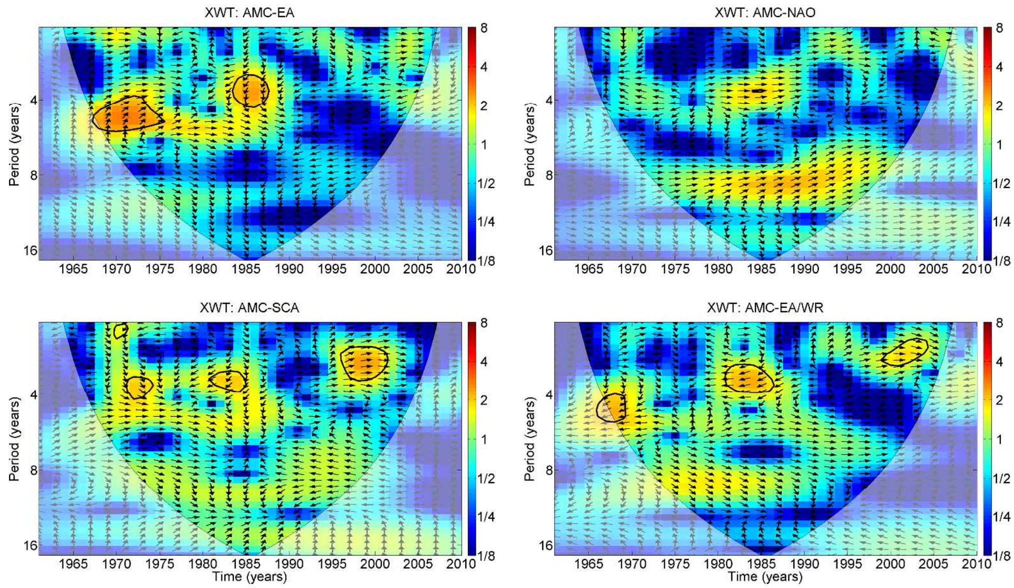


Figure 2: Results of the cross wavelet. Shades denote the dimensionless XWT power spectrum density. Black contour denotes the 5% significance level against red noise. The area where edge effect influence distorts the picture is shown in lighter shades. Arrows denote the phase shift between the time series, pointing to the right if they are in-phase.

1184x682mm (72 x 72 DPI)