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Znanstveni časopis *Hrvatski meteorološki časopis* nastavak je znanstvenog časopisa *Rasprave* koji redovito izlazi od 1982. godine do kada je časopis bio stručni pod nazivom *Rasprave i prikazi* (osnovan 1957.). U časopisu se objavljuju znanstveni i stručni radovi iz područja meteorologije i srodnih znanosti. Objavom rada u Hrvatskom meteorološkom časopisu autori se slažu da se rad objavi na internetskim portalima znanstvenih časopisa, uz poštivanje autorskih prava

Scientific journal *Croatian Meteorological Journal* succeeds the scientific journal *Rasprave,* which has been published regularly since 1982. Before the year 1982 journal had been published as professional one under the title *Rasprave i prikazi* (established in 1957). The *Croatian Meteorological Journal* publishes scientific and professional papers in the field of meteorology and related sciences.
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Doktorska disertacija – Sažetak
D.Sc. Thesis – Extended abstract

OBILJEŽJA I MODELIRANJE URBANOGA TOPLINSKOGA OTOKA

Characteristics and modelling of the urban heat island

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Sažetak: Zbog korištenja umjetnih materijala u gradnji koji imaju bitno različita toplinska svojstva u odnosu na prirodne materijale, u gradskim sredinama dolazi do narušavanja bilance energije, promjena u hidrološkom ciklusu, sastavu atmosfere, itd. Kao posljedica tih promjena, javlja se fenomen tzv. urbanog toplinskog otoka koji se odražava u bitno višim temperaturama u izgrađenom dijelu grada u usporedbi s ruralnom okolinom. U ovom istraživanju analizirana su obilježja i promjene urbane klime Zagreba na temelju mjerenja s meteoroloških postaja, modeliranja urbanim klimatskim modelom te analizom satelitskih podataka. U prvom dijelu ovog rada diskutirane su opažene vremenske promjene klime na temelju podataka mjerenja s četiri postaje na području Zagreba u razdoblju 1960. – 2019. Drugi dio analize urbanog toplinskog otoka Zagreba se temelji na rezultatima urbanog klimatskog modeliranja i analizi utjecaja procesa različitih vremenskih i prostornih skala. Kao jedan od mogućih modifikatora urbane klime Zagreba na većoj prostornoj skali odabrana je Sjeverno-atlantska oscilacija (NAO). Istražen je utjecaj različitih kombinacija polariteta zimskih i ljetnih NAO događaja na promjene i karakteristike toplinskog opterećenja grada. Rezultati impliciraju vlažnost tla kao značajan faktor povezanosti zimskog NAO-a i obilježja ljetne urbane klime. Ta je pretpostavka provjerena analognom analizom s obzirom na vrijednosti standardiziranog oborinskog evapotranspiracijskog indeksa (SPEI). Nadalje, procijenjen je doprinos utjecaja lokalnih promjena u namjeni zemljišta između 1968. i 2012. godine i promjena u klimatskim uvjetima na ukupnu promjenu toplinskog opterećenja grada. Konačno, korištenjem regionalnih klimatskih simulacija modela iz EURO-CORDEX inicijative procijenjeno je očekivano toplinsko opterećenje grada Zagreba u uvjetima buduće klime za scenarije emisija stakleničkih plinova RCP4.5 i RCP8.5.

Extended abstract:
1. Introduction

With the usage of artificial materials in construction, urban areas are experiencing changes in albedo, emissivity, thermal capacity and surface roughness compared to rural surrounding. Due to land-atmosphere interactions through the exchanges of energy and water, any change in land cover can result alterations in surface energy and water balance. Consequently, temperatures in built-up areas can be significantly higher compared to rural surroundings, a phenomenon known as an Urban Heat Island (UHI).

The urban climate is under the influence of processes on different spatial and temporal scales such as global warming, North-Atlantic oscillation (NAO), heat waves, drought, etc. Besides, climate factors as mountains, hills, oceans, seas, lakes and rivers also affect urban climate. However, due to the interactions and feedbacks within the climate system, UHI can affect processes related to mentioned factors such as up- and down-slope circulation, sea-breeze circulation, fog formation, etc. Characteristics of land-cover in the cities also have an important role in modifying urban climate.

Besides large-scale drivers (e.g., teleconnections, atmospheric blocking) and feedbacks (e.g., land-atmosphere interactions), initial conditions (e.g., soil moisture, sea surface temperature, snow cover) are also important for development of extreme events. For example, several studies found that extremely warm European summers were preceded by winter precipitation deficit over Mediterranean area.

Therefore, for specific purposes such as the estimation of the efficiency of certain adaptation and/or mitigation measures, it is important to include as many as possible of the mentioned processes and factors. In this research, the response of Zagreb's urban climate to some global and local modifiers was investigated. First, characteristics and changes in climate classes were determined using meteorological measurements. Further, changes in extreme air temperatures and related indices were analysed. The influence of different combinations of winter and summer NAO on the urban heat load in Zagreb was examined from the perspective of its direct (summer NAO) and indirect (winter NAO) effect. Similarly, the importance of drought conditions not only during but also during preceding summertime was considered. The effects of local impacts were studied through the contribution of urbanization and changes in climate conditions to total heat load change from late 1960s. Finally, future urban heat load was estimated for two climate change scenarios using regional climate projections.

2. Data and methods

General characteristics and changes in the urban climate of Zagreb were analyzed using meteorological measurements, urban climate model and satellite data. Daily data measurements from stations Zagreb-Grič (urban), Zagreb-Maksimir (suburban), Zagreb-Pleso (suburban) and Puntijarka (mountain) in the period 1960–2019 were used. Temporal changes in temperature and precipitation parameters needed for the estimation of Köppen-Geiger climate classes were examined, as well as possible changes in climate classes. For the same set of the stations in the same time period, characteristics and changes in extreme air temperatures were examined by both stationary and non-stationary generalized extreme value (GEV) distribution. For nonstationary models, linear temporally dependent location and/or scale parameters were chosen. Linear trends in extreme temperature indices were estimated using Sen's slope, while its significance was tested with Mann Kendall's test.

Modeling of the urban climate was performed using urban climate model MUKLIMO_3 (dynamical part) combined with cuboid method (statistical part). Such approach enabled spatial and temporal evaluation of the urban heat load and involving of mentioned climate factors and processes that affect the urban climate. Satellite Landsat-8 land surface temperature (LST) data were compared with some of the modeled results.

To investigate winter and summer NAO effect to the climate of Zagreb, principal component based NAO index in the period 1947–2019 was used. Drought conditions were defined by standardized precipitation evapotranspiration index (SPEI) calculated using meteorological data from station Zagreb-Maksimir in the period 1947–2019. Preceding drought conditions were defined by SPEI calculated for the period January–May, while current conditions referred to June–August period.

To examine the contribution of urbanization and changes in climate conditions to total heat load change in Zagreb from late 1960s, land-use data describing city situation in the years 1968 and 2012 were used. Corresponding climate conditions were defined by meteorological data in the periods 1961–1990 and 1991–2020.

Future climate conditions were extracted from EURO-CORDEX data for three selected regional climate models (RCM) initialized by two global climate models (GCM). Two representative concentration scenarios (RCP) were selected: moderate RCP4.5 and worst-case RCP8.5. Period 1981–2010 was used as a reference climate, while expected changes were estimated for two future periods: 2011–2040 and 2041–2070.

3. Results

3.1. Climate characteristics and changes of the area of study

The analysis of changes in climate characteristics at four meteorological stations in the period 1961–2019 revealed that all stations experienced transition in climate class based on the definition by Köppen-Geiger. The first change from boreal-forest to moderate climate had occurred at mountain station Puntijarka due to an increase in temperature of the coldest month (January). At lowland stations, observed changes in climate class were associated with an increase in air temperature of the warmest month (July). Hence, the next climate shift was detected at the urban station Zagreb-Grič where moderate climate with warm summer changed to moderate climate with hot summer. At the other two stations, climate shift occurred around 10 years later.

3.2. Observed changes in extreme air temperatures

Based on the data for the same period, differences in characteristics of extreme air temperatures at selected stations were depicted. The strongest cold and warm extremes were found at the airport Zagreb-Pleso station. This was a result of specific weather situations, as well as characteristics of the station. The lowest minimum air temperatures at the mentioned station could be explained by common winter temperature inversions over Zagreb. On the other hand, the highest maximum air temperatures at this station were the result of several factors like openness of station in terms of its sky-view factor, as well as being surrounded by lawns. Similar characteristics were observed at the suburban station Zagreb-Maksimir. The highest minimum air temperature values at the urban station Zagreb-Grič were partially due to its location and characteristics which are not fully following measuring standards defined by World Meteorological Organization. The lowest maximum air temperatures are observed at the mountain station Puntijarka. The exceedance of maximum (minimum) air temperature above (bellow) the corresponding 5-year return value revealed more (less) frequent occurrence of such events in the later compared to the earlier time period. Consequently, return level curves for non-overlapping 30-year periods showed that for both minimum and maximum air temperatures, higher values correspond to the later period. Additionally, employing nonstationary GEV distribution confirmed the necessity of including temporally dependent location parameter in estimating extreme air temperature return values. Generally, including linear location parameter showed to be more important for maximum than for minimum air temperature. The trend analysis results gave a clear signal of a significant increase in warm and decrease in cold indices. Besides, it was shown that the selection of reference period used for percentile-based indices affects the results of trend analysis by enhancing increase (decrease) in warm (cold) indices when period 1981–2010 (1961–1990) was used as a reference. Still, regardless of period used as a reference, increasing trend in warm summer indices was considerably stronger than corresponding trend in winter indices.

3.3. The effect of North-Atlantic oscillation and drought conditions on the urban heat load

In the first part, the influence of North-Atlantic Oscillation (NAO) on summer climate conditions in Zagreb area was investigated. The combinations of different phases of winter and summer NAO were examined in terms of indirect (lagged) and direct effect. Based on the data measurements from Zagreb-Maksimir station, it was found that the largest heat load is obtained when positive winter NAO is followed by negative summer NAO, and the lowest for the opposite combination. On the other hand, combinations of the same polarity of winter and summer NAO phases resulted in lower changes compared to the mean state, due to its opposing effect over this area. Simulations with MUKLIMO_3 model showed generally good agreement with the station data for the period 1981–2010. The highest heat load was simulated in built-up areas, while the lowest was obtained for areas with vegetation and water bodies. Analysis of NAO effect indicated similar conclusions to those based on the analysis of the station data: the highest heat load increase compared to the mean state was found for positive winter–negative summer NAO combination and the strongest decrease was obtained for the opposite situation (negative winter–positive summer NAO). Our results indicated that not only the amplitude of the heat load, but also its spatial variability is affected by NAO. Thus, for winter–summer NAO combination associated with longer dry conditions, a higher increase in heat load was simulated over regions with vegetation, probably due to suppressed evapotranspiration cooling effect. This result points to soil moisture as a potential factor that affects cooling efficiency of areas with vegetation. This assumption was additionally investigated in a similar way as for NAO events, but with drought conditions using standardized precipitation evapotranspiration index (SPEI) applied on the Zagreb-Maksimir station data. Similarly, as for NAO, the lagged (direct) effect on the summer heat load was examined using SPEI calculated for the period January–May (June–August) period. The results of SPEI analysis supported the conclusions based on the analysis of NAO effect and pointed to the soil moisture as an important factor linking atmospheric conditions and cooling efficiency of green infrastructure. Similar analysis of satellite data of land surface temperature upholded this result.

3.4. The effect of urbanization and changes in climate conditions on the urban heat load

The second part of the modeling analysis was focused on the estimation of contribution of changes in climate conditions and land-use modifications to changes in the heat load. For these purposes, two city land-use situations were defined: earlier city state based on the city structure for the year 1968 and more recent state for the year 2012. Corresponding climate conditions were defined for two standard climatological periods: 1961–1990 and 1991–2020. It is important to mention that climate conditions defined this way consist of both climate change and climate variability components. It was shown that changes in climate conditions dominantly contributed to the amplitude of heat load change, while land-use modifications influenced its spatial variability. The changes in heat load due to climate effect were significant over the whole domain, but for land-use effect significant changes were found only over limited areas, mainly those where some modification in land-use has occurred. Besides, changes in climate conditions resulted in a relatively uniform increase of heat load over lowland parts of the city, while the changes due to land-use modifications were found to be both positive and negative. Generally, an increase in heat load was observed for areas where some of the vegetation classes were replaced by built-up classes and vice versa. Also, obtained results indicate the importance of location of the land-use change (due to its interaction with the surrounding) as well as its form (i.e., grouped or scattered). When analyzing climate effect on changes in heat load, dependence on land-use class was still obtained. Also, slight differences in the heat load response to the changes in land-use were detected for different climate conditions. This result indicates that due to the nonlinear interactions within the system it is not possible to separate climate and landuse effects on changes in heat load.

3.5. Expected future urban heat load

To estimate the heat load in future climate conditions, selected RCMs from EURO-CORDEX initiation were used. Bias correction of RCM data was performed using quantile mapping method in comparison to measurements from meteorological station Zagreb-Maksimir for the reference period 1981–2010. All three variables needed for cuboid method (air temperature, relative humidity and wind speed) were corrected. Comparison of results of urban climate modeling based on the raw and corrected RCM data revealed the importance of bias correction. Generally, cooler and windier simulated conditions of RCMs, lead to underestimated amplitude of heat load and much lower spatial variability compared to the control field obtained using measurements from meteorological station. On the other hand, after bias correction, heat load field in the reference period was well represented for all selected models. The estimation of expected heat load in a future climate revealed a general increase in heat load, however with differences in the amplitudes of projected increase for different RCMs. The increase is expected to be stronger in the later projection period (2041–2070) compared to the earlier one (2011–2040), as well as for RCP8.5 compared to RCP4.5.

4. Conclusion

The results shown in this research point to significant changes in urban climate of Zagreb which generally became warmer. These changes are partially result of climate change and climate variation, as well as due to urbanization and local changes in the city. Detected climate changes, as well as expected increase in the future heat load point to a necessity for climate adaptation and mitigation measures. The analysis of changes in land-use showed that the strongest heat load increase was related to areas where some vegetation areas were replaced by built-up classes, and the strongest decrease for the opposite situation. Such results indirectly indicated the efficiency of green infrastructure in mitigating urban heat load which was widely commented in the literature. As shown in this research, the cooling efficiency of the vegetation depends on the soil moisture conditions. This finding is especially important from the aspect of the predictability of such situations (e.g., via winter and summer NAO modes) which helps in better preparedness of the irrigation system. Besides, expected drier future conditions highlight the importance of well-planned water management and irrigation system.

SADRŽAJ
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