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How extreme precipitation in 2010 altered urban heat island behaviour in Debrecen

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Abstract

Earlier examinations of the urban heat island (UHI) characteristics in Debrecen revealed unusual behaviour in the years 2010 and 2011, while the following years exhibited characteristics expected according to the literature. The year 2010 in Hungary was characterised by anomalously high precipitation with several extreme events, including two Mediterranean cyclones in the spring, numerous convective systems in the summer, and several slow-moving frontal passages in the autumn. These led – both country-wide and in Debrecen – to record-high annual precipitation, and significant deviations in other meteorological elements like soil moisture and near-surface humidity characteristics. It is possible that the development of the urban heat island (UHI) in Debrecen was also affected. This study investigates the unusual behaviour of the UHI in 2010 and early 2011, focusing on how the excessive precipitation influenced the urban climate. Data from 2010 to 2015 were analysed, originally including temperature, humidity, wind, precipitation, cloud cover and soil moisture measurements from a city and a rural station. The current analysis shows that the high precipitation caused significant changes in soil moisture and relative humidity in the rural area, possibly leading to an increased latent heat flux at the expense of sensible heat. This might have reduced the UHI intensity during both day-time and night-time. With this, the study proposes a potential explanation for how long-term high precipitation can have lasting effects on UHI development, which may contribute to a deeper understanding of the interactions between extreme weather events and urban climate dynamics, which is crucial for urban planning and climate adaptation strategies in the context of climate change.

Keywords: urban heat island, precipitation anomaly, Debrecen, extreme weather, climate dynamics, energy balance

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Introduction

Urbanization and climate change are two major factors influencing local and regional weather patterns, particularly in urban environments. One of the most studied phenomena in urban climatology is the Urban Heat Island (UHI) effect, where urban areas exhibit higher air temperature than their rural surroundings, primarily due to modifications in surface characteristics such as reduced vegetation, increased impermeable surfaces, and altered energy balance (Oke, T.R. 1973). This effect is especially pronounced during clear, calm weather conditions, but its behaviour under extreme weather, such as excessive precipitation, remains less understood.

The year 2010 presented an opportunity to investigate the effects of extreme precipitation on UHI behaviour in Debrecen, Hungary. The city, located on the Great Hungarian Plain, experienced significantly

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higher than average rainfall throughout the year, with some months recording up to three times the normal precipitation (Móring, A. 2011). This raised the question of how such excessive rainfall might influence UHI development, given that high precipitation events can alter urban and rural environments' thermal and moisture characteristics.

While the UHI phenomenon has been widely documented, most studies focus on its development during heatwaves or stable, dry weather conditions, and specific impacts of extreme weather, for example a long-lasting high-precipitation event, on UHI dynamics remain largely unexplored. This study aims to address this gap by analysing the unusual UHI behaviour observed in Debrecen during the extreme precipitation year of 2010. The focus is on understanding how excessive rainfall affects the energy balance in both urban and rural areas and how this, in turn, influences UHI development. We compare air temperature, humidity, cloud cover and wind data from 2010 to 2015 from two meteorological stations: one in the urban centre of Debrecen and the other in a nearby rural location. We aim to provide some insights into the mechanism behind UHI modulation in response to a prolonged high-precipitation event.

Ultimately, this research contributes to the broader understanding of urban climatology by highlighting the role of extreme weather in shaping UHI dynamics. The findings are particularly relevant in the context of climate change, where extreme weather events, such as heavy rainfall, are projected to become more frequent and intense. Understanding the interplay between urbanisation, precipitation, and UHI can help inform urban planning and climate adaptation strategists, ensuring that cities are better prepared to cope with the impacts of a changing climate.

Literature review

While the UHI phenomenon has been widely documented in various urban settings, most studies focus on its development during heatwaves or stable, dry weather conditions (Szymanowski, M. 2005; Kovács, A. and Unger, J. 2014; Unger, J. *et al.* 2017). In such cases, urban areas experience enhanced heating due to the prevalence of heat-absorbing materials like concrete and asphalt, reduced vegetation, and lower evapotranspiration compared to rural areas (Oke, T.R. 2002). These factors contribute to a temperature contrast between the city and its surroundings, often peaking during the night when heat release from urban surfaces is slower (Kłysik, K. and Fortuniak, K. 1999). While the literature extensively discusses how UHI affects precipitation (e.g. Han, J.-Y. *et al.* 2014; Marelle, L. *et al.* 2020; Öztürk, S.P. *et al.* 2025), there is limited understanding of the case vice-versa, that is, how prolonged high-precipitation events influence UHI intensity and dynamics, especially when considering the energy balance in urban and rural areas.

In recent years, climate variability has caused a growing frequency of extreme weather events, including both heatwaves and heavy rainfall (Bartholy, J. and Pongrácz, R. 2013). The year 2010 serves as an example of an extreme precipitation year in Hungary and much of Central Europe, where several significant rainfall events contributed to record-breaking annual precipitation totals. Among these events, two Mediterranean cyclones, named Zsófia and Angéla, were particularly impactful, bringing intense and prolonged periods of rainfall (Ujváry, K. 2010; Teknős, L. 2012). These weather anomalies led to flooding in many areas and significantly altered local climatic conditions (Senevirante, S.I. *et al.* 2010; Husain, S.Z. *et al.* 2014; Vereecken, H. *et al.* 2022), including urban areas such as Debrecen.

Typically, in rural areas, heavy rainfall increases soil moisture, leading to enhanced latent heat flux due to higher evapotranspiration rates, which in turn can reduce surface temperatures (Altermann, M. *et al.* 2005). In urban areas, however, much of the precipitation is rapidly drained from the surface due to the prevalence of impermeable surfaces and storm water management systems (e.g. Dobai, A. *et al.* 2024; Kubiak-Wójcicka, K. *et al.* 2025), meaning that the moisture content in the urban environment may not increase to the same extent as in rural areas. This discrepancy could lead to a modification of the UHI effect, as the thermal response of urban and rural areas to precipitation differs. Understanding these dynamics is critical for developing accurate models of urban climate and planning for the impacts of extreme weather events in an era of increasing climate variability.

Several studies have examined the relationship between UHI and weather patterns (Morris, C.J.G. and Simmonds, I. 2000; Beranová, R. and Huth, R. 2005; Hoffmann, P. and Schlünyen, K.H. 2013), but few have focused on the impact of prolonged precipitation on UHI intensity (László, E. and Weidinger, T. 2014; László, E. and Salavec, P. 2018). Research by Schlünzen, K.H. *et al.* (2010) highlights the regional differences in temperature and precipitation in metropolitan areas, suggesting that local climatic conditions can significantly influence UHI behaviour. Similarly, Gedzelman, S.D. *et al.* (2003) observed mesoscale variations in the UHI effect around New York City, showing that localised weather conditions can modulate the intensity of UHI. However, the specific impact of long-lasting high-precipitation weather on UHI dynamics, particularly in smaller cities like Debrecen, remains largely unexplored.

The UHI's general behaviour in Debrecen resembles those of other similar towns on plain areas without large water bodies in the vicinity (Peng, S. *et al.* 2012). Only a few slight differences were found which seem to express more-or-less unique features for Debrecen (Szegedi, S. 2000; Kircsi, A. and Szegedi, S. 2003; Szegedi, S. and Kircsi, A. 2003; Szegedi, S. *et al.* 2010; László, E. *et al.* 2016). These are reflected in our data as well, in the years from 2012 to 2015, when there were no modifying effects caused by either large precipitation or high soil water content.

General characteristics of absolute humidity difference between urban and rural areas is less frequently studied (Kuttler, W. *et al.* 2007; Sherwood, S.C. *et al.* 2010). Due to convective transfer processes typical of the summer half-year, this difference decreases following the afternoon maximum, as convection lifts moisture from the surface to higher layers of troposphere, hence, vapour pressure drops in the surface layers.

Soil moisture data can show how saturated the soil is, which determines the intensity of evaporation. As such, the energy balance can be largely different just by the difference in soil moisture content, while other meteorological elements are the same. For example, the latent heat flux can dominate the sensible heat flux when the soil is saturated. Around an urban environment, the different storage capacity of the urban and rural soils – for example, the existence of drainage systems in the town – causes differences in the modification of latent heat flux in an extreme precipitation event (Starke, P. *et al.* 2010; Huang, X. and Song, J. 2023; Luo, Z. *et al.* 2023). With this, the urban heat island development is also affected (Altermann, M. *et al.* 2005).

We will show that the characteristic behaviour of the UHI in Debrecen was different in the years 2010 and 2011, which is attributable to the permanent high precipitation and the long-lasting saturation of the soil with liquid water. Total precipitation in 2010 reached 964 mm at DVK and 994 mm at AMO. More than half of this was recorded during the period between May and September, causing inland floods around the town. For comparison, Hungarian Meteorological Service reported 546 mm average yearly sum in the period 1991 to 2020 in Debrecen.

Data and methods

The measurements, basis of the results detailed below, were carried out at two sites simultaneously: inside the city of Debrecen (DVK, LCZ-2) and 4.9 km to the northwest at the Agrometeorological Observatory near Kismacs (AMO, LCZ-D), at a distance of 1.8 km from the edge of the urban area (*Figure 1*). The difference between their elevation does not exceed 2 metres. Debrecen, populated by 200,000, is located in the Great Hungarian Plain inside the Carpathi-

Fig. 1. Location of Debrecen Urban Climate Station (DVK, bottom right) at the Institute for Nuclear Research (MTA ATOMKI) and the Agrometeorological Observatory (AMO) of the Centre for Precision Farming R&D Services, University of Debrecen (bottom left) within the satellite map of Debrecen (top). *Source:* Compiled by the authors.

an Basin at an elevation of 120 m above sea level (approx. N 47.5°, E 21.6°). The flat land and the lack of nearby large water bodies favour the development of an urban heat island (UHI).

The urban climate station (DVK) is situated in a densely built-up (78%) zone of Debrecen, within the area of the Institute for Nuclear Research (HUN-REN ATOMKI), 1 km to the north of the city centre. According to classification scheme of local climate zones (Stewart, I.D. and Oke, T.R. 2012), it is classified as LCZ-2 with rather compact, mid-rise buildings and scattered woody vegetation. Data collection was carried out with a Davis 6152 Vantage automatic weather station in the period between 1 January 2010 and 31 December 2015, with very few intermissions. Instruments have been placed at 2 m a.g.l., which meets the recommendations; data obtained during the measurement campaign will well represent the ambient climate (Oke, T.R. 2006). The type of the station is suitable for studies of urban climate as it is equipped with adequate precision temperature (±0.1 °C), humidity (±2%) and wind velocity (±0.1 m/s) sensors.

As a reference, 10-min resolution and high precision data of the Agrometeorological Observatory (AMO) were used, representing the natural climate of the surrounding area (Rácz, Cs. *et al.* 2013).

Since both stations represent the local climate zone in which they are situated, the temperature of the DVK station subtracted from that of the AMO station serves as an appropriate measure of the intensity of urban heat island intensity.

UHI intensity is defined as the difference between the urban and rural temperatures. In our case, only one station was available in both areas, so the actual UHI intensity is defined as the difference $T_{DVK} - T_{AMO}$. However, this is a time series with a resolution of 10 minutes. Since the UHI exhibits a daily course, we define the following UHI intensity indices for each day:

- F-UHI: Full-day averaged UHI intensity (from 0 to 24 CET),
- D-UHI: Day-time averaged UHI intensity (from 5 to 18 CET),
- N-UHI: Night-time averaged UHI intensity (from 18 to 5 CET),
- M-UHI: Maximal daily UHI intensity.

The difference in relative humidity (RH) between the city and rural areas is less commonly studied (Hage, K.D. 1975; Ackermann, B. 1987; Unger, J. 1999; Unkašević, M. *et al.* 2001). The main reason is the need for high-precision sensors, as RH measurements require a more complex technique than that of temperature. In addition, because of the dependence on temperature of relative humidity, differences in the values do not usually mean the same difference in the absolute amount of moisture. For this reason, it is more suitable to involve vapour pressure or other absolute humidity data to highlight absolute differences. Here, vapour pressure was calculated using the 10-min temperature and relative humidity data for both stations.

Measured data of soil moisture was available only from the Agrometeorological Observatory where two sensors measured soil moisture. Both represent approximately the average of the uppermost 30 cm. The soil type is a typical calcareous chernozem. Normally, the volumetric soil moisture content lies around 20 percent, but it is mostly in the range of 15 to 30 percent. Values outside this interval occurs during extremely dry or wet weather.

Results

Urban heat island intensity

In the summer of 2010 and 2011, we observed a weaker development of the urban heat island compared to the following years, which may be explained by the excessive precipitation (Móring, A. 2011). UHI appears during the dawn and day-time hours as well *(Figure 2).* Day-time negative heat island was detectable in September and October, which can be explained by the decrease of precipitation in these months. An unusual pattern was also observable during the drought period in 2011 (see *Figure 2*), so we conjecture that the amount and intensity of precipitation can determine the daily dynamics of UHI. It appeared mainly in late spring to early summer (May: 55 mm, June: 49 mm, July: 266 mm, August: 42 mm) as high precipitation was measured (see Appendix 6 in László, E. 2017), while the course of dawn and day-time UHI deviated from the normal.

Relative humidity and vapour pressure

During the day, high differences may occur in the course of relative humidity *(Figure 3)*. The night-time humidity deficit in the city occasionally dropped as low as 38 percent in comparison with the AMO, however, the most typical values range from -10 to -22 percent. In the day-time, relative humidity was generally 10 to 15 percent higher at the DVK, except for the very low (-6%) difference in the cold season. The highest differences were found during the warm and the transitional seasons, clearly pointing out the seasonal characteristic of the parameter. Furthermore,

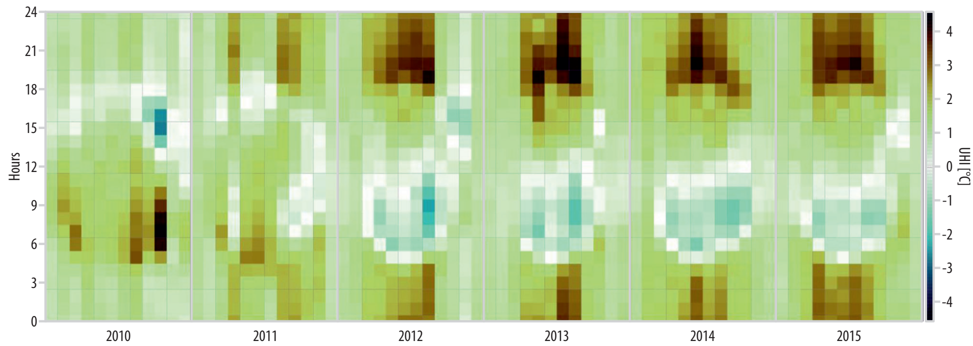

Fig. 2. Monthly averaged daily course of UHI from January 2010 to December 2015. Time of day is on the vertical axis, and one column represents one month. *Source:* Compiled by the authors.

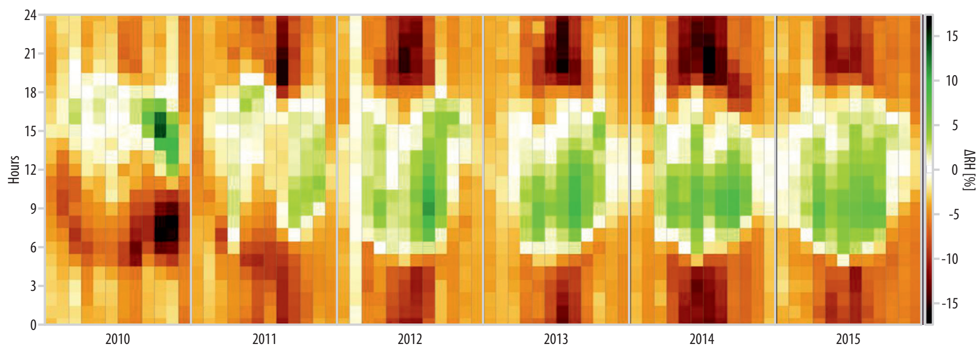

Fig. 3. Monthly averaged daily course of the difference of relative humidity (RH_{DVK} – RH_{AMO}) from January 2010 to December 2015. Time of day is on the vertical axis, and one column represents one month. *Source:* Compiled by the authors.

the pattern of differences in relative humidity in 2010 differs from that of an average year, mainly driven by the extreme rainfall measured that year.

Vapour pressure difference (Δe) between the city and the countryside rarely reaches 1 hPa in winter, while it may exceed 5 hPa in the summer months *(Figure 4).* The effect of convection on vapour pressure can be seen on both the DVK and AMO station data. The absolute humidity curve peaks later inside the city. During the winter half-year convective transfer is less typical, thus, absolute humidity does not show a daily course and only a slight difference is observable between the urban and rural environment.

As a general summary, the contrast between city and countryside may as well be significant and negligible, depending on both the season and the time of day, which is reflected in our data as follows:

Only a slight difference of relative humidity can be measured day-time, while during the night it is less humid in the city.

During the day-light hours, vapour pressure is higher in the rural area. Similar to relative humidity, the daily course of vapour pressure peaks in the afternoon hours (at about 14 CET) in the summer half-year.

After sunset, vapour pressure rapidly drops, causing a vapour deficit in urban areas compared to the surroundings.

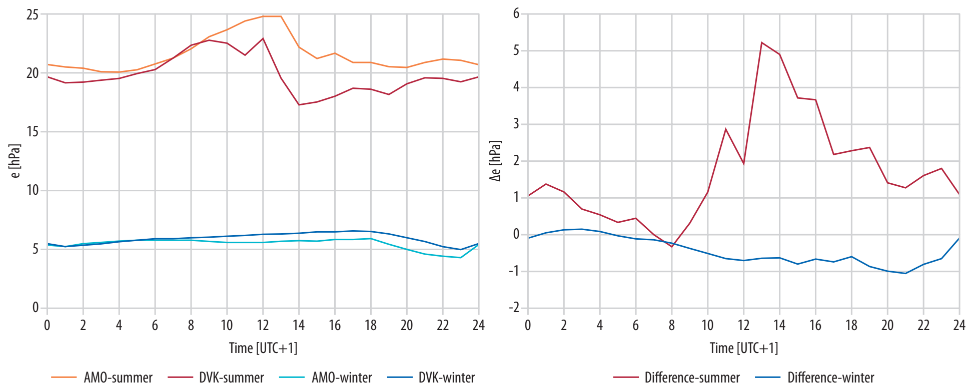

Fig. 4. Vapour pressure course on a typical winter (16.01.2015), and summer (04.08.2015) day at the AMO and DVK stations (left), and their difference ($e_{AMO} - e_{DVK}$) (right). *Source:* Compiled by the authors.

From the dawn hours, vapor pressure rapidly grows at rural locations, which is driven by the intense evapotranspiration and weak convective processes.

The RH difference daily course (see *Figure 3*) shows the normal behaviour between 2012 and 2015. In 2010 and 2011, a similar pattern can be seen as in *Figure 2* for the UHI. The day-time difference between the city and the rural area vanishes. At night, the usual deficit in the city compared to the rural area is less pronounced. In the autumn of 2010, a morning deficit appeared in the city, while in the afternoon, the RH in the city became higher. This is also similar to the UHI pattern in September and October. The slow transition to the usual behaviour in 2011 also appears similar to that of the UHI.

Soil moisture

As can be seen in *Figure 5*, the volumetric soil moisture content is generally in the mentioned interval; higher values occur on days when higher precipitation occurred. Considerably, the water content in these periods can be permanently high, over 30 percent, but these are short periods compared to that lasting until around the middle of 2011. The water content in 2010 and early 2011 is usu-

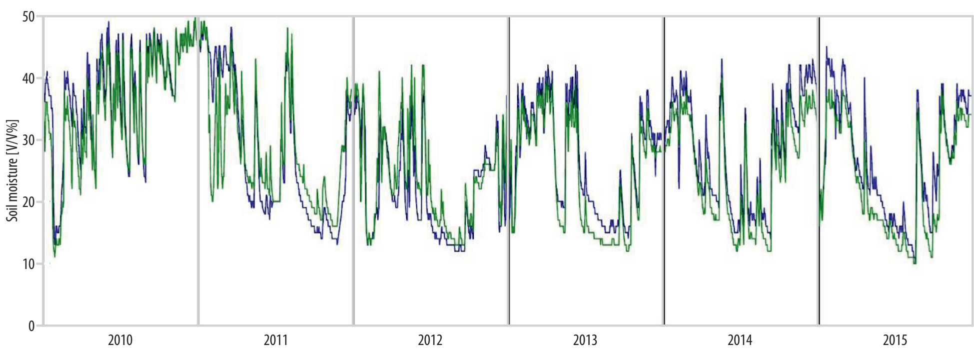

Fig. 5. Soil moisture content time series at the AMO station from two sensors in the upper 30 cm layer. *Source:* Compiled by the authors.

ally higher than in the usual wet periods, around 45 to 50 percent, about the pore space (46.2%, according to Table 9 in Altermann, M. *et al.* 2005). This means that inland flooding should be present in the vicinity before the middle of 2011.

Discussion

The investigation of the urban (DVK) and rural (AMO) measurement data revealed the anomalous behaviour of the urban heat island in 2010 and 2011 in Debrecen, Hungary. In normal years, the night-time urban heat island development is usually strong in summer, while the city is usually cooler in the day-time. In winter, the urban heat island development is weak and nearly the same in the night- and in day-time. In 2010 and early 2011, the urban heat island development was nearly equal or even stronger in day-time than at night. In the dry year of 2011, the transition to normal was smooth, meaning that the urban heat island reacted slowly to the return to normal weather which happened in January 2011. This effect is also revealed by the daily course of the UHI (see *Figure 2*).

Elements which are considered determining factors in advantageous conditions for urban heat island development were briefly analysed earlier, but in this case, only the course of relative humidity difference was modified in 2010 and 2011. The difference in wind and cloudiness cannot change much due to the relatively short distance between the two stations. As such, macro-synoptic changes in weather patterns cannot directly alter the urban heat island development, so extreme precipitation and its consequences are assumed to cause the modification of urban heat island development.

In a typical summer day, the building structure in the city causes the temperature to rise more slowly in the morning than in rural areas, due to shadowing. Thus, the relative humidity remains higher as the absolute humidity is not affected. After the maximum temperature – which is determined by the nearly constant PBL height in a typical fair weather summer day – is reached at the rural area, which is earlier than in the city, the relative humidity difference begins to vanish. As the temperature remains higher in the city at night, the relative humidity becomes lower there. This is true if the vapour pressure has few spatial differences. That spatial difference appears in the afternoon when stronger evapotranspiration makes the vapour pressure rise more in the rural area, as seen in *Figure 4*.

In a high precipitation situation, the high runoff in the city caused by the drainage system and the non-porous surfaces causes the loss of groundwater content. In the rural area, the water is kept in the soil and the high groundwater causes high evapotranspiration which leads to a higher absolute humidity than usual, keeping the relative humidity higher as well. This can make rural RH values equal to, or even in excess of, those of the city. The high RH and the decreased radiation caused by the often cloudy weather can also make the daily course less pronounced.

The similarities of the monthly-averaged daily courses of RH and UHI in 2010 and early 2011 are probably related to the similar patterns in UHI in September and October, the latter can be related to the longer dry period amongst the high precipitation events. However, an explanation of this feature with the available data is uncertain.

In the following winters, the dominating synoptic scale patterns (zonal, meridional, frequent cold pillow situations, etc.) cause complications. The RH difference seems to be more sensitive to synoptic patterns, and one synoptic situation can cover a large part of one winter. As such, the average daily course can be more different from one winter to another, while in the summer, the effect of daily radiation course exceeds that of the synoptic patterns. Thus, the daily course of the RH difference cannot be used to explain UHI behaviour in winter without considering synoptic-scale weather patterns. For example, the apparent inhomogeneity in February 2012 is caused by cold and dry continental air mass lying over the Carpathian Basin for approximately 20 to 25 days.

The effect of high precipitation on humidity can be examined in terms of any humidity characteristic. Relative humidity reveals the difference more pronouncedly because, for example, high relative humidity difference means less difference in absolute humidity in a colder period. Thus, absolute measures are important when considering the energy balance because the absolute humidity is included in the latent heat. When the precipitation, and accordingly the absolute humidity, is high, the latent heat flux rises in the rural area at the expense of the sensible heat flux. The lower sensible heat flux with a similar wind course, however, is only possible if the temperature is lower. This lower temperature can be set up not only by the decreased radiation but also by the higher evaporation of groundwater.

The wet period notably increased the soil moisture and vapour transfer (evapotranspiration) towards the lower layers of the atmosphere at the AMO station. In an urban area, the drainage system removes most of the water content of an excessive precipitation event. The groundwater, in turn, can remain unusually high after a high precipitation period, for a longer time. As the weather returned to normal in January 2011, inland floods were still common in the Great Plain. These survived until spring, partially in the form of ice, and evaporation of these water bodies began only after melting. The ground soil remained saturated until summer, and the evapotranspiration began to decrease in the summer. Soil moisture content measurements at the AMO station are in accordance with this observation, as they show permanently high soil moisture content in 2010 and early 2011, and significantly lower periods afterwards are interrupted with only intermittently occurring high values (see *Figure 5*).

The effect of the high precipitation and the higher humidity on the energy balance is thought to be less in the city because of the loss of groundwater caused by the drainage system and higher surface runoff. This loss of groundwater results in less modification of the vapour pressure. Because of shadowing, the radiation has an effect on the roughness sublayer in the city, meaning that the decreased radiation also has a little effect on the energy balance under the roughness sublayer. That is, the overall modification caused by high precipitation weather is minor. Consequently, the modification of the UHI effect by large precipitation is caused by the modified state of soil, and with that, the PBL, in the rural area. A strong conjecture is, thus, that the modifications in the energy balances caused by the rural soil water anomalies are the key factor in the development of the UHI during (and somewhat after) a high precipitation event.

Hypothesising these modifications of the rural and urban energy balances, it could be concluded that the increased humidity can significantly alter the rural energy balance. As mentioned, this is via the increasing latent heat flux at the expense of the sensible heat flux, leading to a lower maximum temperature and a slower rise of the temperature. This results in a temporal shift in the daily rural temperature course, and this shift is greater in average than the shift between the rural and urban daily temperature courses in normal weather. This explains that the urban area remained warmer in 2010 and early 2011. In the night, the frequently high cloudiness caused higher minimum temperatures at both stations. In rural areas, cloudiness also prevented continuous dew formation, and these two features prevented a stronger temperature decrease in the morning. These lead to more balanced temperatures, i.e. lower UHI intensities at night.

Moreover, a temporally local effect in October of 2010 can be considered on *Figure 2*. The weather then was less cloudy which resulted in increased diurnal amplitude in temperature in the city, causing high UHI values mornings and high negative UHIs evenings.

Conclusions

Examining the urban heat island intensity of Debrecen revealed unusual behaviour in 2010 and early 2011. Anomalous daily courses were observed in which urban heat island was more developed day-time than in the night. Unusually high precipitation characterised the weather of 2010, which often caused inland floods in the vicinity. These survived the winter, and the soil moisture content returned slowly to normal in early 2011, and the normal state of the urban heat island was set up in the summer of 2011. A link between the high precipitation weather and high humidity, and the unusual behaviour of the urban heat island is examined. Measurement datasets of temperature, relative humidity and soil moisture in the city of Debrecen and the nearby Kismacs rural site from 2010 to 2015 are evaluated with the aim of proving the hypothesised link, and to reveal its causes. A possible explanation of the link is provided based on these data. The most possible effect of high precipitation weather is that the unusually high humidity and soil moisture content causes the latent heat flux increase significantly, at the expense of the sensible heat flux, at the rural area in day-time. A more complex effect in the night is probable, tending to be similar to the effect of wet weather in general. In the city, however, these effects are little because of the loss of groundwater caused by the drainage system. This modification of the rural energy balance, thus, resulted in the unusual behaviour of the Debrecen UHI.

Direct measurement to prove the modification of energy balances is difficult to carry out. Difficult on its own because of the expenses of the required measurement technique: a long-term complex micrometeorological measurement campaign is needed at both the rural and urban areas, to track long-term courses of the energy balance components. Furthermore, a similarly exceptional year with high precipitation is needed during which the energy balance is measured as well, but such years occur once in several decades or even centuries. Energy balance measurements may be carried out with continuous control and durable working equipment. Shorter high precipitation weather events, lasting for at least some weeks or months, are not as rare as complete years, and with these measurements available, the effects of this weather on the energy balances and the urban heat island can be examined. Results from such an event of the energy balance can be compared with our hypothesis on the energy balance modification.

While the measurements were carried out before 2016, when urban heat island research was a bit less developed, the techniques nowadays are much more suitable to check these results. As such, a plan might be formulated to develop a measurement network around Debrecen or other town with similar features. If the sensors are readily accessible, the build-up if such a network could be fast enough to capture at least much of the high-groundwater period, as well as the time range when conditions return to normal. This network would include 5 to 10 stations in and around the town, where sensible and latent heat flux could also be measured. The storage of the high-frequency turbulence data seems to be the most problematic in a technical sense.

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