INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **36**: 2111–2119 (2016)
Published online 24 August 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4458

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Short Communication

Observed urban effects on precipitation along the Dutch West coast

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ABSTRACT: Expansion of urban areas has profound effects on land surface characteristics. As such, the land surface can exert influence on atmospheric parameters that might alter precipitation amounts or patterns. In this study, precipitation observations near urban areas along the West coast of the Netherlands are investigated throughout the 1951–2010 period. An innovative analysis methodology is used to deal with the small and fragmented urban areas in the Netherlands. The results show that daily precipitation totals downwind of urban areas are, on average, about 7% higher than precipitation in the rest of the Dutch West coast. Precipitation enhancements up to 20% are found depending on wind direction and time period. These results are comparable with studies from around the globe and show that the influence of relatively small fragmented urban areas, as are present in the Netherlands, can be similar to the influence of large metropolitan areas on precipitation.

KEY WORDS The Netherlands; rainfall; urban effects; land–atmosphere interactions; urban precipitation island

Received 3 April 2015; Revised 19 June 2015; Accepted 28 June 2015

1. Introduction

The influence of urbanization and land use changes on different climate aspects has become a thoroughly investigated issue (e.g. Mahmood *et al.*, 2014). While the effects of urban areas on temperature are well understood (Oke, 1982; Arnfield, 2003), the effects on precipitation are not as straightforward. On one hand, cloud microphysical processes in response to increased (ultrafine) urban aerosols may reduce rainfall (e.g. Givati and Rosenfeld, 2004; Junkermann *et al.*, 2011). On the other hand, local dynamics and thermodynamics associated with an urban heat islands (UHI)-induced convergence zone and more convective boundary layer may enhance urban rainfall (e.g. Shepherd *et al.*, 2002; Han and Baik, 2008). During the 1960s and 1970s, the topic of urban effects on precipitation received ample attention in the United States after the discovery of the La Porte weather anomaly (Changnon, 1968), and the extensive field observation programme METROMEX was initiated (Changnon *et al.*, 1977; Ackerman *et al.*, 1987). Both observational studies and modelling work have been conducted meanwhile, and recommendations for future research have been made (see e.g. Lowry, 1998; Shepherd, 2005; Han *et al.*, 2014 and references therein).

Taking heed of these recommendations, this article investigates urban effects on precipitation in the Netherlands. Days are stratified with a circulation type classification, according to month/season, and occurrence in an early or later stage of urbanization. The Netherlands is a relatively small and flat country with a marine climate located in the northwest of Europe. Individual cities are not larger than 20 km in diameter and lie in close proximity to each other. Our study area is therefore not comparable to the metropolitan areas where previous studies have been conducted. Despite their relatively small size, Dutch cities do influence the atmosphere and UHIs over 5 °C have been measured (Steeneveld *et al.*, 2011; Wolters and Brandsma, 2012; van der Hoeven and Wandl, 2015). The effects on precipitation have not been investigated however. Although extensive knowledge on UHI and urban effects on precipitation exists elsewhere, extrapolations to the Dutch situation are difficult to make due to every location's unique setting (Schluenzen *et al.*, 2010).

Dutch annual mean precipitation varies spatially from 675 to 925 mm (Overeem *et al.*, 2009). In spring and autumn, a distinct but reversed difference between precipitation near the coast and precipitation further inland exists. In spring (autumn), rainfall is more abundant inland (along the coast). This seasonal cycle in coastal precipitation is well linked to the land–sea temperature contrast (Lenderink *et al.*, 2009), but other effects (like atmospheric stability) are likely to be important as well (Attema and Lenderink, 2014), and urbanization might be one of them.

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The objective of this study is to quantify the influence of Dutch urban areas on precipitation by the development and use of an innovative methodology that addresses the cities small size and mutual proximity.

Investigating urban effects in the whole of the Netherland is inappropriate, because most of the major cities lie along the West coast. When sampling precipitation near urban areas, one would inadvertently sample coastal precipitation gradients too. So we face the persistent challenge in urban meteorological research of disentangling the effect of urban areas from the effect of open water sources (Landsberg, 1981). This challenge is dealt with by investigating urban effects up to 45 km from the shoreline, where the coast-inland precipitation gradient is minor (Daniels *et al.*, 2014). This region is of additional interest because it has experienced a larger increase in precipitation than the rest of the country in the last century (Buishand *et al.*, 2013). The investigated region hosts approximately 6 million inhabitants (CBS and PBL, 2011) and is about 5300 km^2.

The utilized data are presented in the next section, while Section 3 presents the novel methodology designed to deal with the fragmented urban areas in the Netherlands. Subsequent results for the time period 1951–2010 are shown in Section 4. The results are positioned into a broader context in Section 5 and conclusions follow in Section 6.

2. Data

2.1. Urbanization trend

Historical land cover maps (HGN) for the Netherlands are available for 1960, 1970, 1980 and 1990 (Kramer *et al.*, 2010). Having these detailed maps available for different time periods is important because the Netherlands, like many countries in Europe, has substantially rebuild and expanded its urban areas after World War II (Diefendorf, 1989). The 1951–2010 period is therefore divided into six periods of 10 years for the analysis. For each 10-year period, the urban extent is determined based on the land use map at the end of the period. For the years 2000 and 2010, the national land cover maps (LGN) version 4 (Wit, 2003; Hazeu *et al.*, 2011) and 6 (Hazeu *et al.*, 2010), respectively, are used. All maps are available at a 25-m resolution. The legends of the HGN and LGN maps differ, and the urban classes given in the HGN maps are split into several classes in the LGN maps. To avoid discontinuities in the urban extent over time, a selection of urban related classes is made (Table 1).

Table 1. Historical/national land use map classes included in the urban extent.

HGN	LGN4	LGN6
5: Buildings and roads	8: Greenhouses	8: Greenhouses
9: Built-up	18: Urban built-up	18: Primary built-up
10: Greenhouses	19: Buildings in rural areas	19: Secondary built-up
11: Baarlenassau	22: Forest in densely built-up	20: Forest in primary built-up
	25: Major roads and railways	23: Grass in primary built-up
	26: Buildings in agricultural areas	25: Major road and railways
		26: Buildings in rural areas

2.2. Circulation type classification

Individual days are stratified using a circulation type classification, computed with the ‘cost733cat’ software (Philipp *et al.*, 2010, 2014). Mean sea level pressure (MSLP) data from ERA-20C at 1200 UTC are used as input for the area 47.25°–57.75°N and 3°–12.75°E. We use the ERA-20C reanalysis dataset, instead of the more commonly known ERA-Interim for example, because it is available over the entire investigated 1951–2010 period. The Jenkinson–Collison types classification scheme (Jenkinson and Collison, 1977), that provides an objective reproduction of the Lamb weather types (Lamb, 1950; Jones *et al.*, 1993), is used. This scheme determines geostrophic wind flow characteristics using MSLP data from 16 points in the area of interest. The resulting classification has eight weather types (WTs) representative of the prevailing geostrophic wind direction (W, NW, N, NE, E, SE, S and SW, where W = 1, …, SW = 8) and one with light flow.

2.3. Precipitation

Precipitation measurements are available from the National Meteorological Institute (KNMI). Measurements are taken every morning at 800 UTC at about 320 stations. Approximately 60 of these stations lie in the West coast and their altitude ranges from 6 m below to 18 m above mean sea level. In each 10-year period, those stations with more than 80% data availability are selected for analysis.

3. Method

Examples of typical methods for evaluating urban effects on precipitation have been schematically depicted by Shepherd *et al.* (2002) and Huff and Changnon (1972). Positioned in relation to the mean wind vector, they encompass the upwind control area, central urban area and downwind area (with the maximum impact area), or simple geometric buffer constructions (e.g. Ashley *et al.*, 2012). While these sorts of analyses are feasible for large (American) cities with relatively unpopulated surroundings, they are unsuitable in the heterogeneous urban landscape of the Netherlands with its many relatively small cities in close proximity. Due to this, it is difficult to investigate a single city and predefine the up- and downwind area in the Netherlands, because the up- and downwind area would interfere with other cities or would be located in the North Sea.

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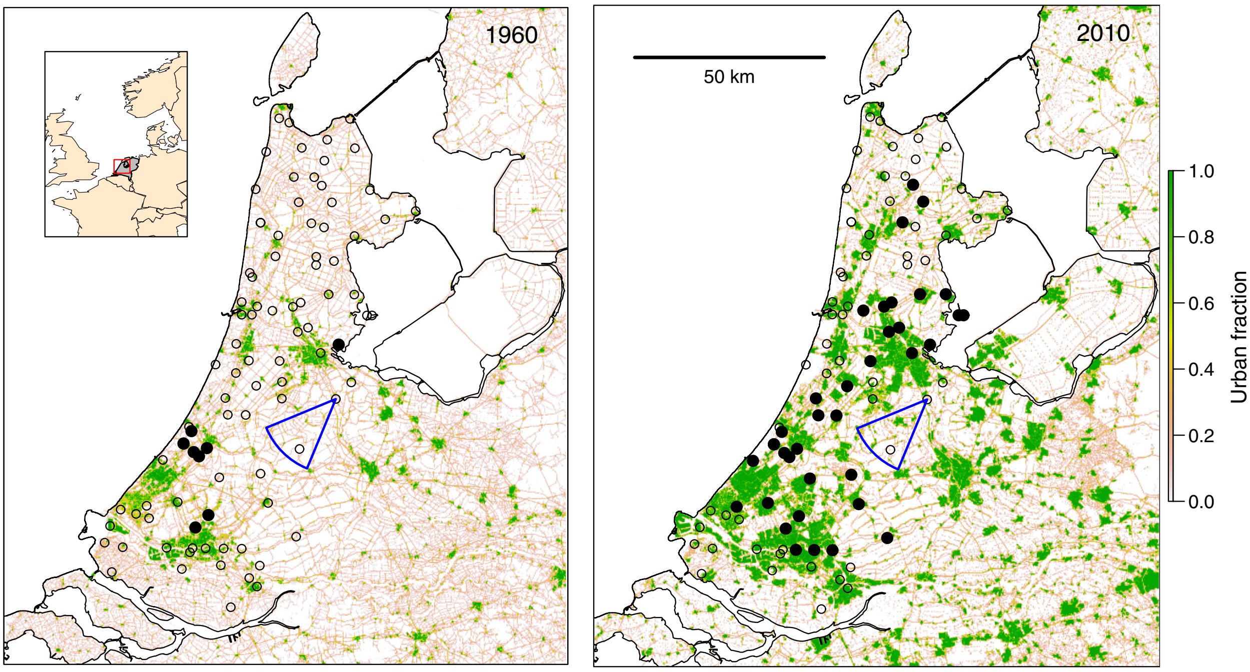

Figure 1. Urban fraction in the northwest of the Netherlands in 1960 (left) and 2010 (right) showing precipitation stations classified as 'urban' (closed circles) and 'rural' (open circles) based on their upwind urban fraction in the one-eight circle with a 20 km radius in the prevailing geostrophic wind direction (here weather type 8, implying SW winds).

In this study, we select stations downwind of urban areas and compare with all other stations in the selected region. This is done separately for each WT so whether a station is selected as urban or rural depends on geostrophic wind direction. For each station, the urban fraction in the upwind area is determined based on a one-eight circle with a 20 km radius (Figure 1). For WT 9 (light flow), the urban fraction is determined in the whole of the circle. Stations with more than 0.25 urban fraction in the upwind area are considered 'urban'. Setting a threshold like this increases the number of urban stations throughout time (Table 2). Consequently, in the 1950s, only 4 of 57 stations are selected as urban, while 22 of 59 are selected in 2000–2010. The remaining stations (i.e. all stations with an urban fraction equal to or lower than 0.25) are classified as 'rural'. A sensitivity analysis for the number of stations and radius size, for both a quarter and one-eight circle, is given in the discussion section.

Mean precipitation is calculated separately for each month and each WT. Where possible, a bootstrap interval is computed to get an estimate of the associated uncertainty. Bootstrapping is done by randomly sampling (with replacement) from the appropriate number of stations (Table 2) and redoing the calculations. This procedure is repeated 1000 times for both urban and rural stations and the 5 and 95th percentile are shown as confidence bands in the appropriate figures. Extreme precipitation is investigated by pooling all data from urban or rural stations together and taking the 95th percentile.

4. Results

This article will mostly show mean values, while the underlying data have a large spread, because of the variable nature of precipitation. In an example of this spread (Figure 2), the most extreme (>12 mm) values lie well above the 1:1 line. While this is not a generality, extreme precipitation is on average more enhanced than mean precipitation downwind of urban areas (Section 4.2.). In Figure 2, urban precipitation is about 11% higher than rural precipitation, and this is on the high end of the outcomes

Table 2. Total number of stations and number of stations classified as urban for each weather type (geostrophic wind direction) in each of the 10-year periods ending with the year indicated.

Year	Number of stations	WT1	WT2	WT3	WT4	WT5	WT6	WT7	WT8	WT9
1960	57	5	7	2	5	2	2	4	4	0
1970	57	10	10	6	9	7	5	10	9	2
1980	60	11	16	11	13	8	10	12	14	5
1990	62	13	15	12	13	10	12	14	15	5
2000	57	13	17	17	18	21	17	19	20	13
2010	59	20	17	21	25	25	22	22	24	24

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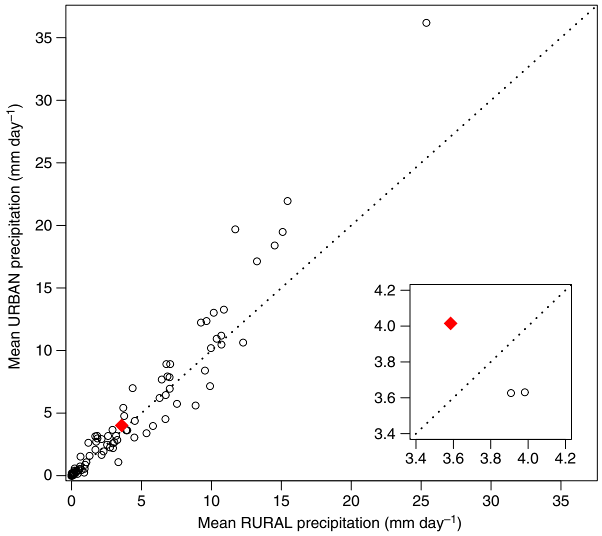

Figure 2. Scatterplot of daily mean summer (JJA) precipitation (mm day^{-1}), averaged over all urban and rural stations, respectively, for weather type 8 (SW wind) in the period 2001–2010. The average is given as a diamond and zoomed into in the inset.

(Section 4.1.). The next section will focus on mean precipitation amounts like these, thereafter a few examples of other precipitation metrics like the distribution and rate are provided. Detailed results for the period 2001–2010 will be shown while other periods will be summarized because they are similar.

4.1. Mean precipitation

Mean precipitation is on average higher at urban stations than at rural stations in eight of the nine WTs (Figure 3). The only exception is for north-easterly winds (WT 4), when precipitation at rural stations is about 2% higher. This relative difference (given in the top left of each figure panel) is calculated from the frequency weighted yearly means of urban and rural precipitation. The occurrence frequency of the combination WT-month is given by the grey bars. This makes it easy to see westerly (SW, W, NW) winds are much more frequent than easterly (NE, E, SE) winds and have higher precipitation on average. Of the total 108 WT-month combinations, urban precipitation is higher in 92, and rural precipitation in 16. So although

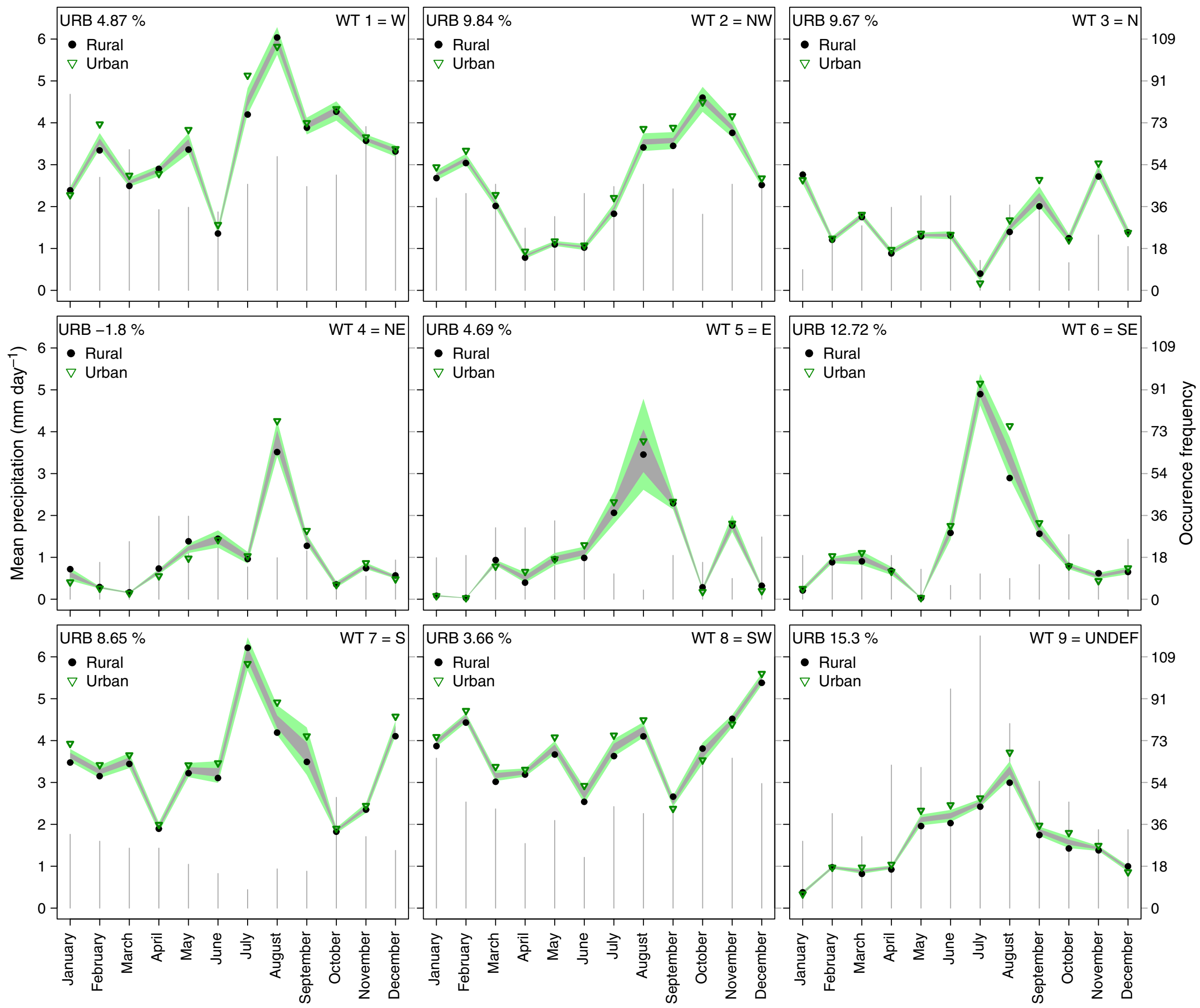

Figure 3. Mean daily precipitation (mm day^{-1}) at urban and rural stations for each weather type (geostrophic wind direction) throughout the year over the period 2001–2010. Light green and dark grey bands show the 90% confidence intervals, based on a bootstrapping procedure, for urban and rural precipitation, respectively. The grey bars show the frequency of occurrence of each WT-month combination.

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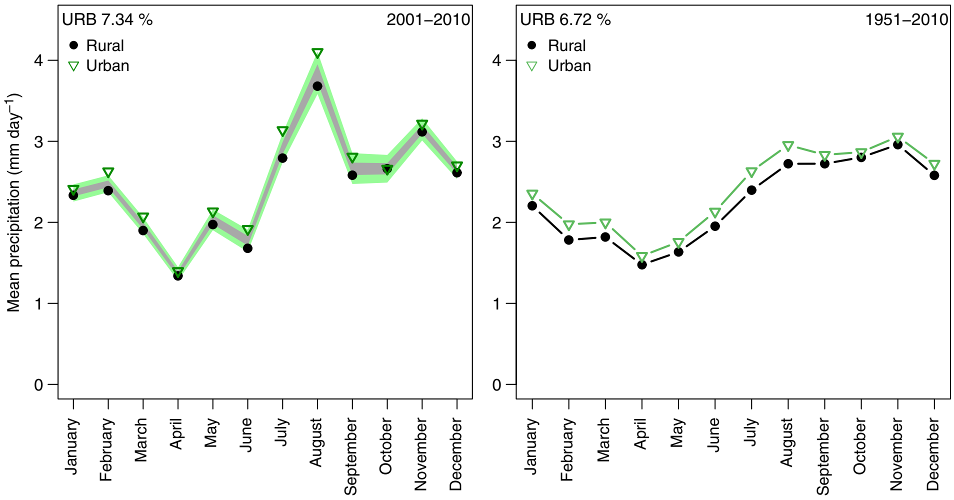

Figure 4. Mean daily precipitation (mm day^{-1}) at urban and rural stations throughout the year over the period 2001–2010 (left) and 1951–2010 (right). Light green and dark grey bands (left) show the 90% confidence intervals, based on a bootstrapping procedure, for urban and rural precipitation, respectively, that cannot be estimated for the entire period (right).

there is some variation, urban precipitation is higher in the vast majority of cases.

The yearly cycle of urban and rural precipitation aggregated over all WTs is given in Figure 4. Urban (green) triangles lying above the light green band indicate confidence in the results that urban precipitation is enhanced, while rural (black) dots lying under the dark grey band give confidence that rural precipitation is lower than expected by chance. Over the 2001–2010 period (Figure 4, left), the difference between urban and rural precipitation is rarely significant, but urban precipitation is rather consistently higher. This enhancement is largest in the summer period [12% in summer], and about 4, 8 and 6% in autumn, winter and spring, respectively. Similar results are obtained for the other 10-year periods and the entire period (1951–2010, Figure 4, right), indicating these are robust results, not dependent on the investigated time period. When analysing the entire 1951–2010 time period, bootstrap intervals cannot be easily computed because the number of stations varies over time.

The average urban enhancement throughout the entire period is about 6% when WT 9 is not taken into consideration and 7% when it is. WT 9 cannot be taken into account in the 1951–1960 period because no stations are classified as urban because the urban fraction is always below the 0.25 threshold. Urban precipitation in WT 4 (NE) and 5 (E) can be up to 10% lower than rural in some 10-year time periods (Figure 5). These instances when urban precipitation is lower generally happen in the less frequently occurring easterly WTs and, therefore, have limited influence on the mean. The largest positive urban effects are found under light flow (WT 9). We hypothesize this is

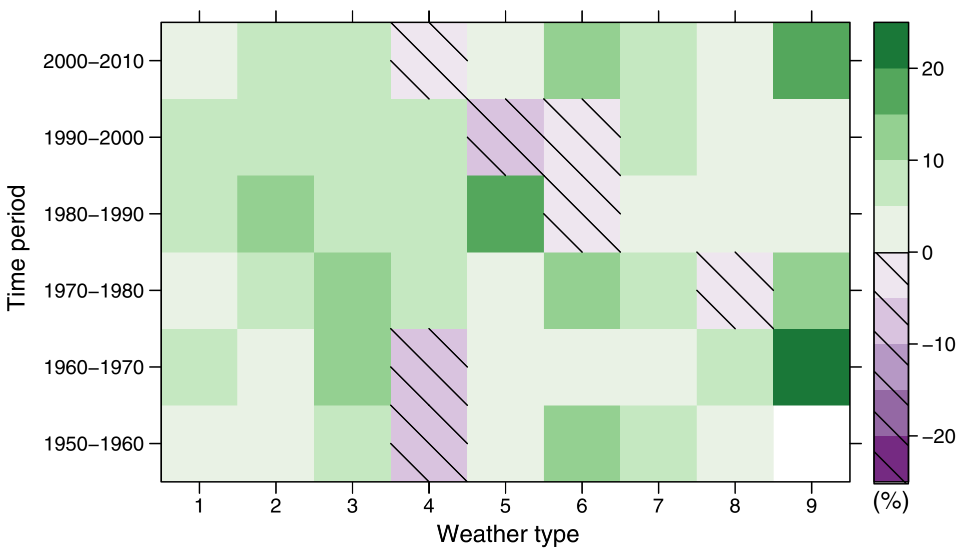

Figure 5. Relative difference between mean precipitation at urban and rural stations (%) for each weather type (wind direction) and 10-year period ending with the year indicated. Hatching marks negative values.

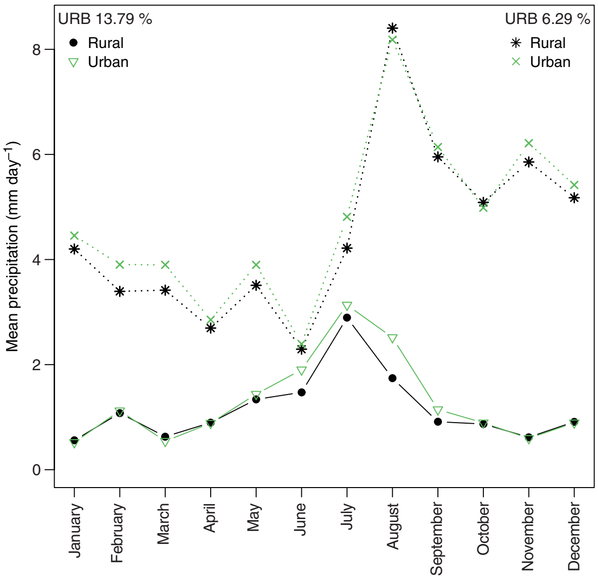

Figure 6. Mean daily precipitation (mm day^{-1}) at urban and rural stations throughout the year over the period 2001–2010 for days with the 20% lowest wind speeds (dots, triangles, solid lines) and 20% highest wind speeds (stars, crosses, dashed lines).

because more convective precipitation occurs in this WT and this type of precipitation is more susceptible to triggering by the land surface.

In addition, the strength of the urban enhancement of precipitation is larger at low wind speeds (Figure 6). To investigate this, we use average 10 m wind speed from ERA-Interim over the central Netherlands (i.e. a 0.5×1 degree area centred around 52.5°N and 3.5°E). Average precipitation is much higher at high wind speeds (>7.2 ms^{-1}), but the relative urban enhancement is larger (13.8%) at low wind speeds (<3 ms^{-1}). The enhancement at low wind speeds is only seen in the summer half year (May–September). At high wind speeds, the urban enhancement is seen throughout the entire year, but it is relatively small in summer. The 20 km distance that is used to determine urban stations might be too small for use under high wind speeds as clouds could cover this distance, or more, within the time that precipitation forms and as such limit the urban enhancement calculated here. Moreover, at low wind speeds the air mass overlying urban surfaces stays in place for a longer period of time and hence can be influenced more. Consequently, the relatively high sensible heat flux and updrafts over urban areas could provide the trigger for the formation of precipitation. Additionally, the high levels aerosols associated with urban areas are more likely to impact nearby precipitation at low wind speeds.

4.2. Other indices

A similar enhancement to that found in mean precipitation is also found in other precipitation indices. The figures for extreme precipitation (95th percentile of the pooled urban and rural data) are remarkably similar to those for mean precipitation in all time periods. The urban enhancement is somewhat lower (6%) in the latter 2001–2010 period than over the entire 60-year period (11%) (Figure 7). Similar to mean precipitation, the differences are largest (10%) in summer and smallest (3%) in autumn.

We also investigate the distribution of precipitation for urban and rural stations (Figure 8). This can be done without any averaging because the data are simply pooled together. The difference in distribution between the seasons is caused by the more convective character of precipitation and higher moisture content of the atmosphere in summer, and more frontal character and lower moisture content in winter. For both winter and summer, urban precipitation consistently lies above rural precipitation throughout the entire distribution except for the very tails. The tails however consist of little data (the ten most extreme data points are indicated by dots) and are therefore uncertain.

Finally, to examine whether enhanced aerosol loading due to urban areas played a role, the weekly cycle of

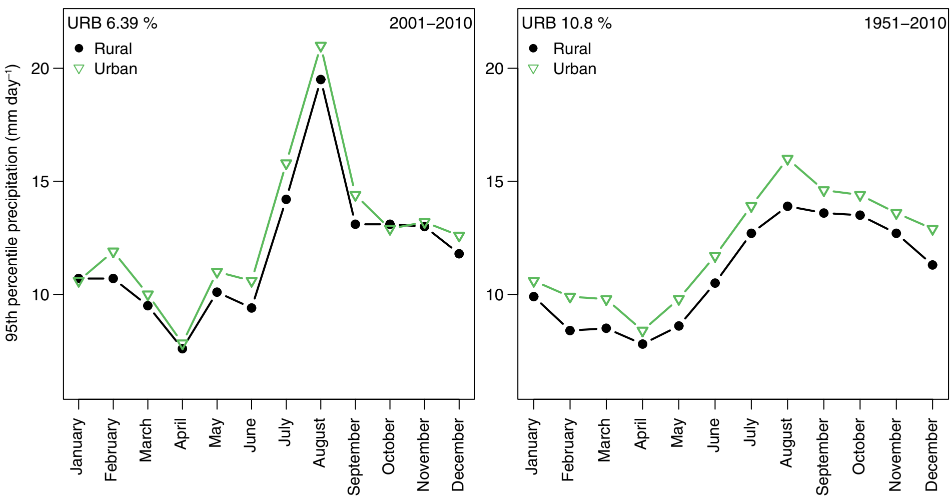

Figure 7. Mean extreme precipitation (95th percentile, mm day^{-1}) at urban and rural stations throughout the year over the period 2001–2010 (left) and 1951–2010 (right).

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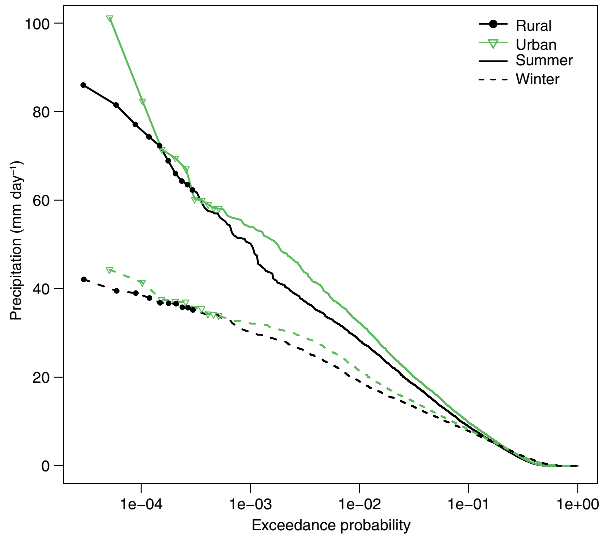

Figure 8. Rainfall (mm day^{-1}) exceedance probability at urban and rural stations in summer (JJA) and winter (DJF) over the period 2001–2010.

precipitation was investigated. The existence of a weekly cycle has more often been used as evidence of human activities on climate (e.g. Arnfield, 2003; Kanda, 2007; Rosenfeld and Bell, 2011; Stallins *et al.*, 2013). However, following the methodology of Stjern (2011), we could not find any evidence of a weekly cycle in precipitation along the Dutch West coast or the Netherlands as a whole.

5. Discussion

The selection of urban and rural stations in this study is a crucial step in the methodology of this article. Nevertheless, a sensitivity analysis shows that using different criteria for selecting urban stations, a smaller or larger influence radius or a different angle (90° instead of 45°) for the selection area, only influences the strength and not the sign of the observed urban effect (Figure 9). The number of 'urban' stations varies here from 5 to 35, always selecting those stations with the highest urban fraction. Note that the 0.25 urban fraction criterion that is used throughout the rest of the article does not apply here, and a fixed number of stations is used. Ultimately, it seems the enhancement of precipitation downwind of urban areas is robust (i.e. always positive), but it could be biased by the selection method because some stations are classified as urban more often. The reason these stations have higher precipitation amounts could be due to the nearby urban areas or other factors (e.g. the influence of the North Sea). To test this, the calculations for the 2001–2010 period are repeated 1000 times, but now with a random WT for each day. The resulting distribution indicates an average urban effect of 4.5% ($\sigma = 0.5\%$), that the actual calculated urban effect of 7.3% falls well outside of. Therefore, there is a small, but significant precipitation enhancement at the stations downwind of cities, that we can certainly attribute to urban influence.

Other studies show that the chosen method can have substantial impact on the calculated size of urban effects. For example, average precipitation downwind of St Louis in spring (autumn) was found to be 14% (7%) enhanced using regional pattern analysis (Huff and Changnon, 1986), while using a quadrant method total precipitation in spring (autumn) was found to be 4% (17%) enhanced (Changnon *et al.*, 1991). The mean urban precipitation enhancements we find for the Dutch West coast over the entire 1951–2010 period are 9, 10, 3 and 8%, respectively, for spring, summer, autumn and winter. These magnitudes are comparable to the aforementioned enhancements at St Louis and other large metropolitan regions (e.g. Huff and Changnon, 1973; Jauregui and Romales, 1996; Ashley *et al.*, 2012). In our study, we find the lowest enhancement in autumn (3%), and this is quite dissimilar to other studies and is probably related to the coastal effects of the North Sea. Another Dutch study has compared radar data of precipitation within urban areas to that in the rest of the country. For the period 2009–2012, it seems that high intensity events (>25 mm in 15 min, >60 mm in 60 min) occur somewhat more often within urban areas (Overeem, 2014). Although this is a very different methodology, these results seem to be in agreement with the observed difference in precipitation distribution at urban and rural stations in this study.

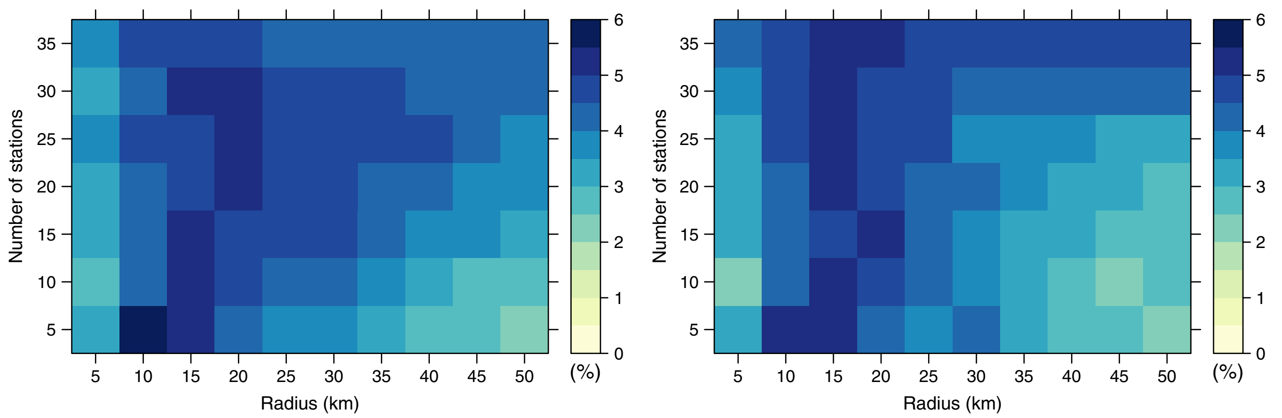

Figure 9. Relative difference between mean precipitation at urban and rural stations (%) averaged over the period 1951–2010 for a fixed number of stations with the highest urban fraction, using different radius sizes of a one-eight circle (left) and a one-quarter circle (right) used to determine the upwind urban fraction.

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All the same, mean precipitation has increased by about 25% near the Dutch coast in the period 1951–2009 (Buishand *et al.*, 2011). Urban areas might have contributed to this increase, but they are unlikely to be the major cause because we only find an enhancement of 7% along the most populated West Coast. Therefore, other factors such as the enhancement of sea surface temperature (Attema and Lenderink, 2014) or changes in circulation (Haren *et al.*, 2013) must also be responsible for the observed trend. In addition, the increase of coastal precipitation is smallest in July–September, while the enhancement downwind of urban areas is strongest in these months. Nevertheless, the area that is influenced by urban areas is presently much larger than in the past. Where cities made up approximately 14% of our investigated region in 1960, they covered almost 33% of the region in 2010, and the affected region must have non-linearly expanded in the meantime as well.

6. Conclusions

In this article, precipitation near urban areas in the densely populated coastal region in the West of the Netherlands is investigated with a novel methodology over the time period 1951–2010. Individual Dutch cities are not larger than 20 km in diameter, but many of them lie in close proximity. To deal with this fragmented urban area, different stations were determined 'urban' or 'rural' for every (i.e. geostrophic wind direction). Stations were classified as urban if the fraction of urban area in the upwind region was above 0.25, and the amount of urban stations therefore increases through time.

Based on daily station observations for the 1951–2010 period, we find a consistent year-round precipitation enhancement of about 7% downwind of urban areas along the Dutch West coast. This enhancement is seen throughout the entire distribution of precipitation, so in extreme precipitation as well as the mean. The effects are seen for nearly every weather type (WT), and the relative difference between urban and rural stations remains moderately constant throughout time. The largest urban–rural differences are found under light flow (WT 9) and low wind speeds, suggesting that enhancement of precipitation is favoured under convective conditions. In all, we find our methodology deals well with the fragmented urban areas in the Netherlands and the influence of such type of urbanization can be similar to that of a large metropolitan region.

Acknowledgements

This study was supported by the Dutch research program Knowledge for Climate. We thank two anonymous reviewers for their constructive comments on an earlier version of this manuscript.

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