RESEARCH ARTICLE

Analysis of urban rainfall from hourly to seasonal scales using high-resolution radar observations in the Netherlands

Iris Manola[1] | Gert-Jan Steeneveld[2] | Remko Uijlenhoet[3] | Albert A. M. Holtslag[2]

[1]Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, the Netherlands

[2]Meteorology and Air Quality Section, Department of Environmental Sciences, Wageningen University, Wageningen, the Netherlands

[3]Hydrology and Quantitative Water Management Group, Department of Environmental Sciences, Wageningen University, Wageningen, the Netherlands

Correspondence
Iris Manola, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, the Netherlands.
Email: manola.irida@gmail.com, i.manola@uva.nl

Funding information
Nederlandse Organisatie voor Wetenschappelijk Onderzoek, Grant/Award Number: 864.14.007; Wageningen University and Research Centre

Abstract

In this article an analysis of urban rainfall from hourly to seasonal scales is conducted for the Netherlands, with a focus on its capital, Amsterdam. In addition, the potential of synoptic weather types and local wind directions to categorize extreme rainfall in Amsterdam is assessed. An analysis of gauge-adjusted daily radar rainfall retrievals with 1 km spatial resolution for 10 years shows that rainfall is enhanced over Dutch cities compared to their rural surroundings, with a maximum of a 14.2% increase over the largest cities in winter. The annual cumulative rainfall in Amsterdam appears to be significantly higher compared to its surroundings. This is due both to the higher frequency of occurrence of urban rainfall and to the higher hourly mean intensities. Extreme hourly rainfall rates appear to be affected by urban areas only in summer. Diurnal and weekly rainfall cycles do not reveal any significant urban influence. A wind direction analysis reveals that extreme rainfall events can primarily be attributed to westerly and next to southerly air masses. An analysis of the Jenkinson and Collinson (JC) and the German Weather Service (Deutscher Wetterdienst, DWD) weather types with rainfall and extreme rainfall events reveals that the JC weather types are more indicative of situations associated with rainfall extremes, whereas the DWD weather types are more indicative of situations resulting in higher accumulated rainfall amounts.

KEYWORDS
extreme rainfall, rain radar observations, synoptic weather types, urban rainfall

1 | INTRODUCTION

Extreme precipitation events over urban areas cause substantial damage in infrastructure and economy as well as disruptions to society (Koks *et al.*, 2015), while extensive urbanization can alter the land-surface characteristics that influence the atmospheric variables affecting precipitation (Shepherd *et al.*, 2002). Due to climate change, the frequency and intensity of extreme precipitation is projected to increase in many parts of the world (e.g., Pachauri *et al.*, 2014; Stocker, 2014), while urban areas are also expanding rapidly (Seto *et al.*, 2012). Designing future climate-resilient cities requires detailed spatiotemporal precipitation information over cities and a better understanding of how local urbanization influences precipitation.

The Netherlands is a small, low-elevation country in North-Western Europe (Figure 1b). It hosts the large deltas of the Rhine, Meuse, and Scheldt rivers and therefore is prone to fluvial, pluvial, and coastal flooding. According to the Dutch climate scenarios (Van den Hurk *et al.*, 2014), the
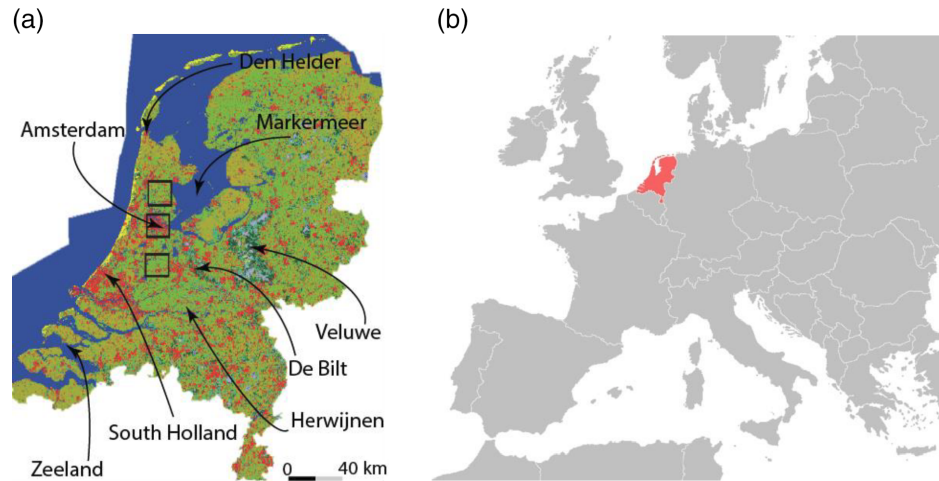
(a) (b)

FIGURE 1 (a) Land use map of the Netherlands. Red colours indicate urban land use, and green colours indicate rural land use, according to the Land Use Database of the Netherlands (LGN database, Hazeu *et al*., 2011). The middle black box shows the location of Amsterdam, and the boxes north and south of the city show the selected rural areas. Other locations are indicated by the arrows. (b) The map of Europe with the position of the Netherlands in red. The complete list of the LGN colour bars can be found at https://www.wur.nl/nl/Onderzoek-Resultaten/ Onderzoeksinstituten/Environmental-Research/Faciliteiten-Producten/Kaarten-en-GIS-bestanden/Landelijk-Grondgebruik-Nederland/lgn_ viewer.htm

2-m temperature is projected to rise by 1–2.3°C between 2014 and 2050, and precipitation extremes are projected to become more frequent and more intense. Spatial coverage of urban areas along the Dutch west coast has expanded from 14% in 1960 to 33% in 2010, coinciding with increased precipitation downwind of urban areas (Daniels *et al*., 2016a). Extreme precipitation events can cause large disruptions in the Netherlands, such as the event of July 28, 2014, which had a return period of 5–15 years (Van Oldenborgh and Lenderink, 2014; Manola *et al*., 2018) and lead to flooding, property damage of €10 M, as well as widespread traffic disruption. Because the most severe damage is often reported in urban areas (Ward *et al*., 2013) and because Dutch cities are continuously growing, it is essential to develop knowledge of the detailed climatological characteristics of precipitation and to better understand the urban influence on precipitation, especially for the Dutch capital, Amsterdam. Amsterdam is a special city due to its morphology, location near the coast, and its typical pattern of concentric canals.

Four objectives form the main sections of this article: (a) perform a seasonal analysis of precipitation in the Netherlands for the current decade and discuss the observed urban influence; (b) analyse in detail the precipitation in Amsterdam from hourly to seasonal time-scales; (c) identify rainfall patterns that can be attributed to urbanization; and (d) assess the potential of local and synoptic variables regarding the identification of extreme precipitation in Amsterdam, as extreme precipitation requires favourable atmospheric conditions. The local variable is the wind direction and the synoptic variables are two weather-type classifications that differ with respect to their objective classification method and geographical area.

The importance of the wind direction during precipitation lies in the indirect identification of the moisture sources (Eden *et al*., 2018). Such information can serve as a prognostic tool, in a similar manner as the weather types (WTs), in order to identify extreme events.

Niyogi *et al*. (2017) stated that reported inconsistencies in past studies concerning urban precipitation mechanisms might be the result of models or gridded data products of low resolution. One asset of this analysis is that it uses the high spatial and temporal resolution time series of the Dutch radar rainfall observations that are available for 10 years at 1 km spatial and 1 hr temporal resolution, which makes it possible to calculate extreme precipitation statistics (Overeem *et al*., 2009b).

This article is organized as follows: Section 2 introduces background information that motivates and explains this work. The data and methods are described in Section 3. The natural and anthropogenic patterns of seasonal precipitation in the Netherlands are discussed in Section 4. Section 5 presents the annual, weekly, and diurnal precipitation cycles in Amsterdam. Section 5 also discusses the observed influence of urban areas on those variables. Subsequently, the relation of wind direction (Section 6) and WTs (Section 7) are related to mean and extreme precipitation. Finally, a summary and discussion is provided in Section 8.

2 | BACKGROUND

Precipitation is a highly intricate process; therefore, untangling the impact of urbanization on precipitation is not

straightforward. Changes in the surface morphology, surface air temperature, surface energy balance, moisture availability, wind, and aerosol composition can inhibit or enhance the formation, intensity, and duration of precipitation or alter its trajectory. For example, the urban heat island (UHI) can initiate or enhance the convective activity over cities and enhance precipitation over and downwind of urban areas (Han and Baik, 2008; Shem and Shepherd, 2009; Yang et al., 2016). Conversely, the UHI can cause precipitation to decrease downwind of a city, as a storm may bifurcate due to building-barrier effects (Dou et al., 2015). Moreover, it was also recently shown that urbanization can significantly enhance precipitation during a hurricane (Zhang et al., 2018). The cloud microphysical processes due to increased urban aerosols may either reduce (Rosenfeld, 2000; Givati and Rosenfeld, 2004; Rosenfeld et al., 2007; Junkermann et al., 2011) or increase precipitation (Li et al., 2011), depending on the size and concentration of the nuclei and the precipitation type (Schmid and Niyogi, 2017). Aerosols are reported to experience a weekly cycle related to the alternation of transportation and work during weekdays with leisure activities during weekends. Similar variations are reported in temperature related to anthropogenic heat release (Simmonds and Keay, 1997; Forster and Solomon, 2003). These weekly variations are likely to influence precipitation on a weekly cycle that depends on the aerosol type and concentration, the region, the season, and the precipitation type (Cerveny and Balling, 1998; Bäumer and Vogel, 2007; Gong et al., 2007; Bell et al., 2009; Yang et al., 2017).

The general occurrence of extreme precipitation events depends strongly on the weather conditions prior to and during the event (Kron et al., 2012; Santos et al., 2015). Therefore, the relation between atmospheric patterns and precipitation has been studied extensively (Andrade et al., 2011; Burt and Ferranti, 2012; Raziei et al., 2013). These investigations often have focused on identifying the circulation patterns associated with extreme rainfall in different areas in Europe, such as the Mediterranean Basin (Goodess, 2000), France and Spain (Obled et al., 2002; Bárdossy and Filiz, 2005; Queralt et al., 2009), Portugal (Trigo and DaCamara, 2000), the United Kingdom (Wilby and Quinn, 2013), Greece (Tolika et al., 2007), the Alps (Parajka et al., 2010; Horton et al., 2017), Germany (Petrow et al., 2009), and Central Europe (Jacobeit et al., 2006). Most such studies have shown that the occurrence of extreme precipitation can be related to so called "weather types," which are defined as the classification of synoptic atmospheric circulation states into distinct types. For example, Trigo and DaCamara (2000) found that preferred synoptic conditions lead to severe weather and concluded that WTs can be useful in the detection of moisture sources involved in extreme precipitation. Therefore, identification of WTs may assist in extreme precipitation forecasting

(Queralt et al., 2009). However, such an analysis is still lacking for the Netherlands and the city of Amsterdam.

The Netherlands is a low-lying country in the mid-latitudes with maritime climate with precipitation in all seasons and a temperate summer (Köppen and Geiger, 1928), with the North Sea to the north and west (Figure 1a). Amsterdam, the Dutch capital, is the largest Dutch city; its metropolitan area is about 12 km across and has about 1 million inhabitants. Its urban morphology consists of medium-rise buildings, relatively rich vegetation, and open water bodies. The weather of Amsterdam is dominated by the marine air from the North Sea.

In the Netherlands, the prevailing westerly winds transport moisture from sea to land, thus inducing relatively higher precipitation along the coast than inland (Buishand et al., 2009; Overeem et al., 2009b). The sea surface temperature (SST) significantly influences precipitation, as both statistical analysis and model integrations have shown (Lenderink et al., 2009), while other parameters, such as atmospheric stability and land-sea temperature contrast, also play a role (Attema and Lenderink, 2014). This coastal influence is particularly strong in the first 50 km inland. Over the past half century, the coastal areas have consistently become wetter compared to the inland areas, in agreement with the positive SST trend since the 1950s (Van den Hurk et al., 2014). During the past century the annual precipitation has increased by 25%, with a winter and summer increase of 35 and 16%, respectively (Buishand et al., 2013). For the years 1961–2014, an analysis of extreme precipitation indices showed that this increase is associated with a positive trend in the magnitude and frequency of the extremes, especially in recent years (Golroudbary et al., 2017). These trends are related to changes in large-scale atmospheric circulation, SST changes (van Oldenborgh et al., 2009; van Haren et al., 2013) and land-use changes, such as increased urbanization (Daniels et al., 2016a; 2016b). The 2-m air temperature in the Netherlands rose by 1.8°C in the past century, a rate exceeding the global average (Van den Hurk et al., 2014). This has led to an increase of 12% per degree in the hourly intensity of extreme precipitation. At the same time, significant UHI values have been measured in Dutch cities, defined as the urban canyon surface air temperature minus the rural air temperature (e.g., Steeneveld et al., 2011; Koopmans et al., 2015). When comparing daily to annual observations between urban and rural stations in the Netherlands, the increase in extreme indices of the urban stations is relatively higher, although the patterns of change are similar (Golroudbary et al., 2017).

Schmid and Niyogi (2013) concluded that city size affects precipitation, with maximum urban modification happening over cities with around 20 km radius when passing thunderstorms are driven by moderate winds, as then enough time is offered for the urban properties to be fully

communicated into the thunderstorm. The impact was found to decrease linearly with decreasing city size and did not change further for larger cities. However, observations have shown that even relatively small Dutch cities appear to influence daily precipitation amounts (Daniels *et al.*, 2014). An analysis of daily station precipitation data for the years 1951–2010 along the west Dutch coast, where the majority of Dutch cities are located shows a year-round precipitation enhancement of about 7% downwind of urban areas, with a maximum increase in the summer (Daniels *et al.*, 2016b). The advance of the current study stems from the use of gridded radar data at high spatial and temporal resolution, which provide direct observations in the urban areas allowing for better quantitative rainfall estimates over large areas, better statistics and higher precision in the detection of extremes and of short duration and local rainfall events, such as typical convective events.

3 | DATA AND METHODS

3.1 | Radar observations

Hourly rainfall accumulations are obtained from the weather radar rainfall product of the Royal Netherlands Meteorological

Institute (KNMI) (Overeem *et al.*, 2009a; 2009b), with a pixel area of ~0.9×0.9 km^2 for the years 2008–2017. The radar rainfall depths are based on composites of reflectivities from two Dutch weather radars, one located at De Bilt (which was later moved to Herwijnen) and one at Den Helder (locations shown in Figure 1a). The dataset is validated and adjusted with the use of two independent rain gauge networks, an automatic network and a manual network of ~350 gauges in total, evenly spread around the country. The adjustment method can be found at Overeem *et al.* (2009a). The radar data availability is 99.7% and the quality is suitable for hydrological and climatological studies (Overeem *et al.*, 2009a; Brauer *et al.*, 2016).

Some radar artefacts are known, such as an artificial dark straight line south of the radar in Den Helder and some artificial lines in the southwest of the country (Zeeland, see Figure 2). These artefacts are due to beam blockages caused by obstacles in the vicinity of the radars and they can be more pronounced in winter, due to the often lower height of clouds. The analysis that follows in Section 4 was repeated without the region of Zeeland to conclude that the artefacts have an insignificant influence on the outcome. Another artefact is the broad bright circular band centred around the radar in De Bilt in the winter months. This is caused by the radar beam intercepting the melting layer of precipitation,
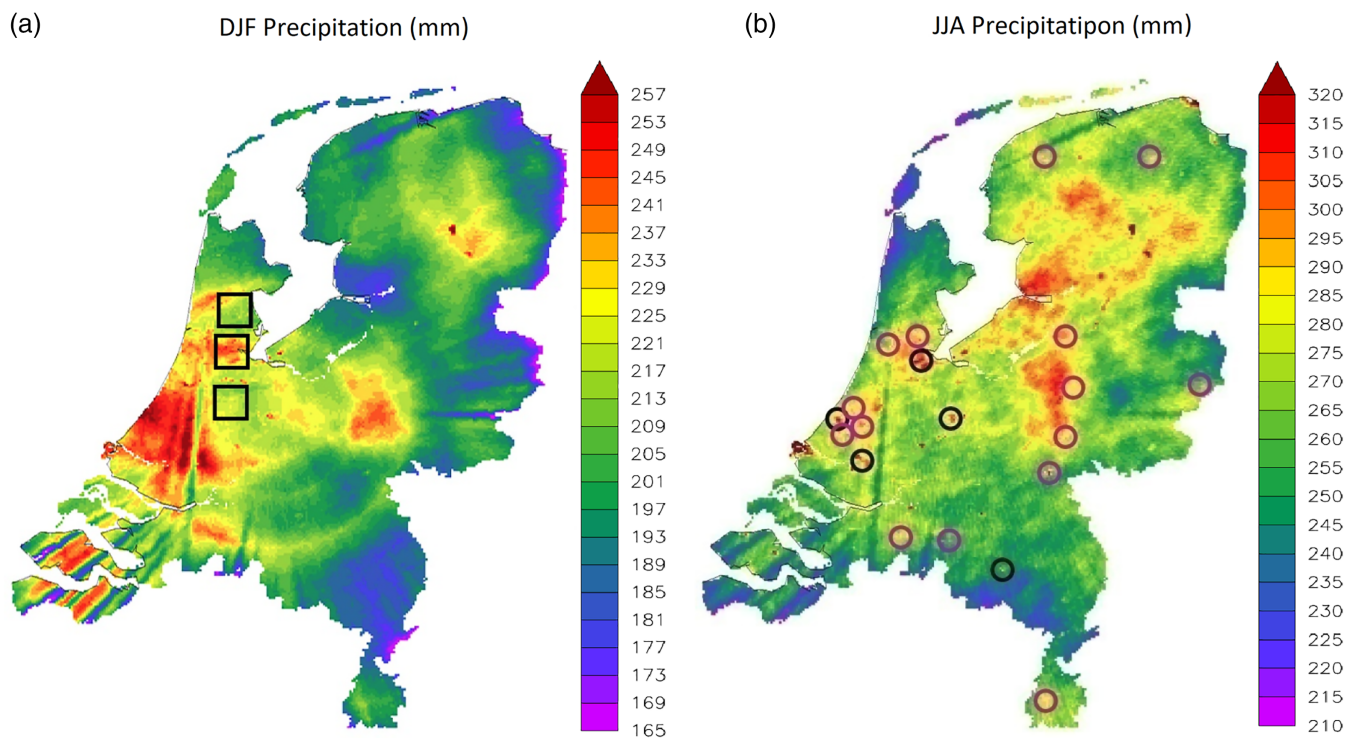

(a) DJF Precipitation (mm)

(b) JJA Precipitatipon (mm)

FIGURE 2 Observed seasonal mean precipitation for the years 2008–2017 in mm (a) for winters and (b) for summers. Note that the colour scales in the two plots differ to match with the maximum of each season. In (a) the three black boxes indicate the location of Amsterdam and the selected southern and northern rural areas, as shown in Figure 1a. The black circles in (b) indicate the locations of the five largest Dutch cities, and the purple circles indicate the following 15 largest cities. The five largest Dutch cities are Amsterdam, Rotterdam, The Hague, Utrecht, and Eindhoven. The 15 smaller cities are Groningen, Tilburg, Breda, Nijmegen, Enschede, Haarlem, Zoetermeer, Leiden, Arnhem, Delft, Zwolle, Leeuwarden, Apeldoorn, Maastricht, and Zaandam

which gives rise to high radar reflectivity factors and thus the "bright band." In January 2017, the radar in De Bilt was discontinued, and a new one was installed in Herwijnen. Since then, the signal has been unaffected by beam blockages, and the overall quality has improved. We note that the study area in Amsterdam and the neighbouring rural areas (see Section 3.2) did not coincide with the areas of the radar artefacts (i.e., the higher reflectivity circle and the beam blockages), as seen in Figure 2. Therefore, the data quality is considered adequate for the current study.

3.2 | Data selection

A common technique for assessing the influence of urbanization on precipitation is by analysing data for the centres, upwind and downwind areas of large cities, by the distances from the city centres, or by dividing the data in concentric circles around the cities (Shepherd *et al*., 2002; Ashley *et al*., 2012; Dou *et al*., 2015; Niyogi *et al*., 2017; Yang *et al*., 2017). These methods are ideal for large cities where the countryside is relatively unpopulated, such as some American or Chinese cities. The Netherlands, though, is a small, densely populated country, comprised of many relatively small cities and towns in their direct vicinity. Therefore, if such methods would be applied here, the rural areas would be affected by neighbouring cities (Daniels *et al*., 2016a). Instead, two rural areas north and south of Amsterdam and the Amsterdam metropolitan area were selected (represented by the rectangle areas above in Figure 1a). The three equally sized areas contain 120 grid points of radar precipitation data each (~10 km × 12 km, representing the urban area of Amsterdam) and are located at comparable distances from the west coast to ensure that they experience an equal marine influence, although the northern rural area and Amsterdam both have the Markermeer Lake as their eastern boundary (location shown in Figure 1a). The two rural areas are located at the maximum possible distance from their surrounding urban areas while also remaining in the vicinity of Amsterdam to assume statistically similar weather conditions. To create more robust statistics, the outcomes of the two rural areas were combined. The resulting comparison between urban and rural data is issued to assess the influence of urbanization on precipitation for the different timescales considered.

In this study, an hour with precipitation is defined separately for each selected area as each hour with more than 0.1 mm of rainfall on average in more than 50% of the selected surface area of the area. The duration of a rain event is measured as the number of consecutive hours during which precipitation occurred in the defined area. It should be noted that the results of the analysis are not particularly sensitive to small changes in the definition of precipitating hour.

3.3 | Wind and WTs

Hourly wind directions are derived from the KNMI automatic weather station nearest to Amsterdam (Schiphol airport). Two WT classifications are also employed, namely the Jenkinson and Collinson classification (JC, http://www.weathertypes.info) and the German Weather Service classification (Deutscher Wetterdienst, DWD, Bissolli and Dittmann, 2001). The two methods differ in the objective classification scheme and the area over which they are applied. The JC classification uses an objective scheme to classify the daily circulation according to the Lamb WTs, with 26 daily synoptic patterns based on the NCEP daily average surface-level pressure data, which follow the Jenkinson and Collinson (1977) system. Each classification is determined around the British Isles by geostrophic surface wind direction and strength (eight wind directions and a zero wind classification) and by cyclonality (cyclonic, anticyclonic, and neutral). The DWD WTs consider 40 objective synoptic daily patterns around Germany. The DWD's daily data base is given by the operational forecast models of the German Meteorological Service at 1200 UTC. The classification is determined by the wind direction (four wind directions and a zero wind), the cyclonality (cyclonic or anticyclonic at 950 hPa and at 500 hPa), and the humidity as the vertical integration of the water vapour content yielding the mean precipitable water in the troposphere (wet or dry classification).

4 | SEASONAL DUTCH PRECIPITATION

4.1 | Spatial patterns

The analysis of the gauge-adjusted radar observations for the years 2008–2017 in the Netherlands shows that the annual precipitation varies in time from 790 to 915 mm on average, and ranges locally in the country from 600 to 1,200 mm for these years. The seasonal cumulative precipitation averaged over the years for summers and winters (Figure 2) shows regional patterns that can mainly be explained by differences in land use, topography, and distance from the sea.

The region of high precipitation in the central-eastern area of the country is the Veluwe, an elevated, forested area (location shown in Figure 1a). This area receives more precipitation than its surroundings because of the forestation and the local higher elevation, even if this elevation is at maximum 100 m, as stated in Ter Maat *et al*. (2013). In that study, model simulations indicated that during winter the

effect of the forest is stronger due to the convergence of moisture during frontal conditions, while during summer the effect of the elevation is stronger because convective conditions are prevailing.

4.2 | Urban influence on Dutch precipitation

The Dutch cities studied in this work are indicated in the small black circles in Figure 2b and range in size from a radius of 2–7 km and in population from 100,000 to almost 1 million inhabitants. It is intriguing to see that the cumulative precipitation over the majority of the cities is higher than over the surrounding countryside. Schmid and Niyogi (2013) found that large, high-rise, and densely built cities significantly influence precipitation. Our results suggest, however, that even relatively small cities with medium-rise buildings and substantial amounts of green spaces and open water bodies can influence precipitation. This statement is supported by a comparison of the total precipitation of the 20 largest Dutch cities and the relevant rural precipitation elsewhere (Figure 3 and Table 1). For this study, the cities are divided into two groups—the five largest cities and the following 15 largest. The boundaries of the cities are defined

by the rectangular areas that enclose the urban areas of each city. The remaining land is considered rural. Among rural land, areas exceeding elevation of 35 m of height are excluded to avoid spurious signals resulting from orography. Those areas are mainly the forested area of the Veluwe and small areas in the east and south of the country.

Overall our results show that precipitation is increased over cities, influenced both by city size and season. The highest precipitation amounts are observed over relatively large cities in winter (up to 14.2% excess precipitation) and in spring (up to 11.7% excess precipitation). Over smaller cities during summer and autumn, the urban–rural contrasts in precipitation are less pronounced (up to 6.6% excess precipitation). The level of significance is assessed with a Kolmogorov–Smirnov and with a Kruskal–Wallis test. For those tests, the total annual and seasonal precipitation for all years is taken into account for all pixels from large cities, small cities, and urban areas. The test indicates that the differences are statistically significant at the $p < .05$ level for both small and large cities for all seasons individually. Overall, precipitation over the five largest Dutch cities is on average enhanced by 10.9% compared to the rural Netherlands, and over smaller cities is enhanced by 5.5%.
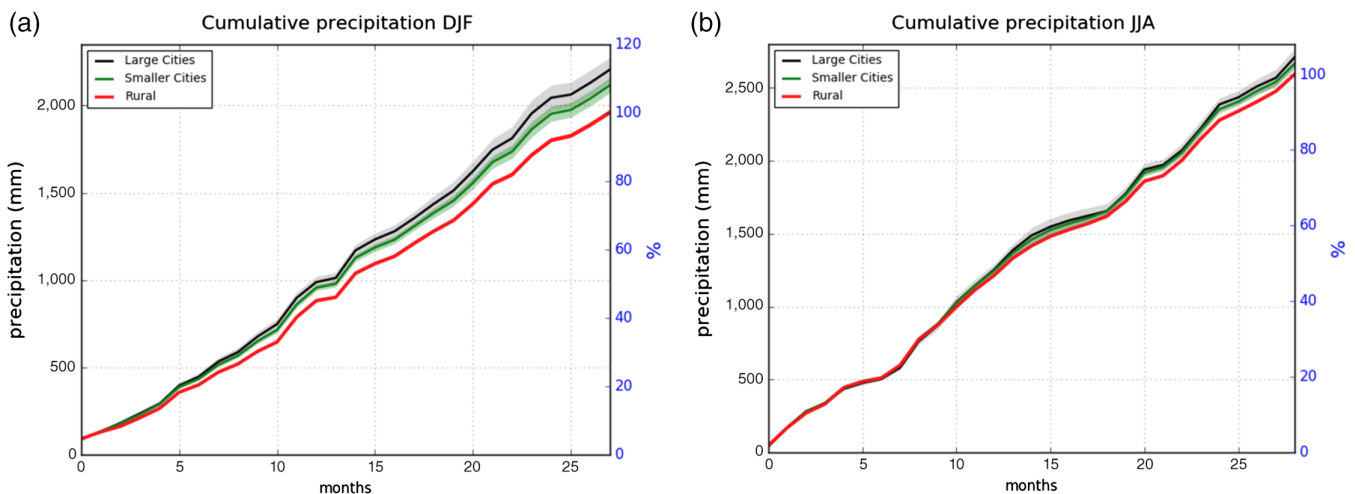

FIGURE 3 Observed cumulative precipitation in mm for the years 2008–2017 averaged over the five largest cities (black line), the 15 next largest cities (green line), and the rural areas (red line), (a) during winters and (b) during summers. The blue axis on the right side indicates the percentage of precipitation, where 100% is the total rural precipitation. The shaded areas indicate the standard error values between the cities in each group. The count of the months on the *x*-axis in (a) starts with the first winter month in 2008 and ends with the last winter month of the dataset, January 2017. Respectively, in (b) the count of the summer months starts in June 2008 and ends in August 2017

Cumulative rainfall	All year (%)	DJF (%)	JJA (%)	SON (%)	MAM (%)
Large cities	10.90	14.20	6.60	6.00	11.70
Small cities	5.00	5.60	3.90	4.70	5.40
All cities	5.50	10.50	5.50	5.00	7.00

TABLE 1 Relative precipitation enhancement (%) between cities and the rural Netherlands

Notes: The cities are grouped for the entire year or the different seasons in (a) the five largest, (b) the following 15 largest, and (c) all cities. All numbers are statistically significant, with $p < .05$. DJF, December - January - February; JJA, June - July - August; SON, September - October - November; MAM, March - April - May.
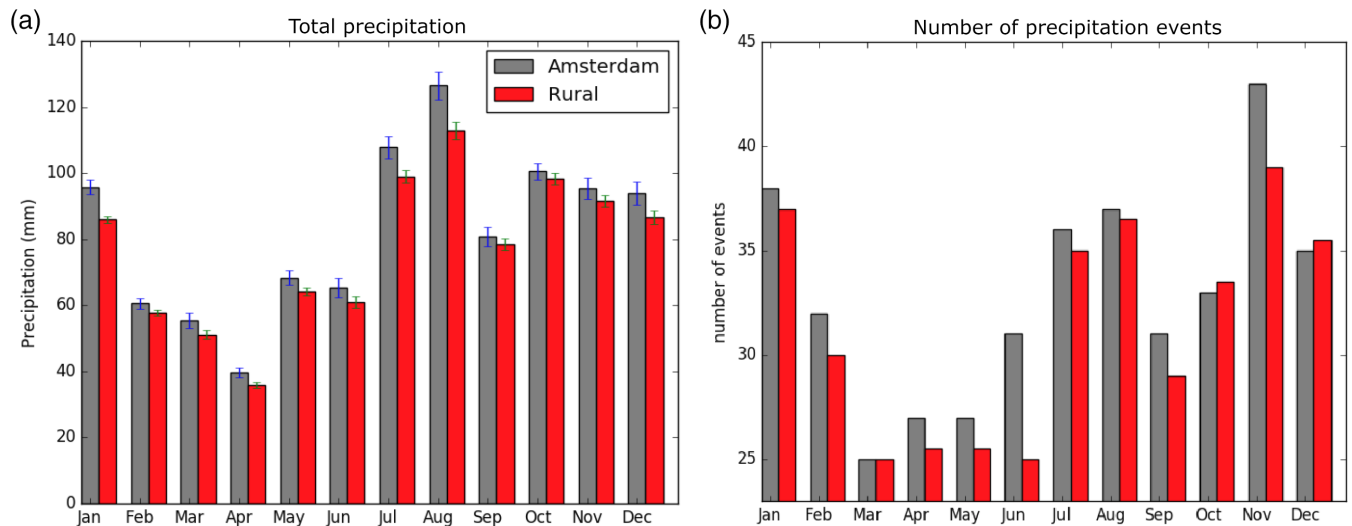
FIGURE 4 Monthly precipitation averaged over the years 2008–2017. The data in red is for Amsterdam, and the averages of the two rural areas are in blue. Chart (a) presents the monthly cumulative precipitation in mm. The bars indicate the bootstrapped 95% confidence intervals. Chart (b) presents the average number of precipitation events per month
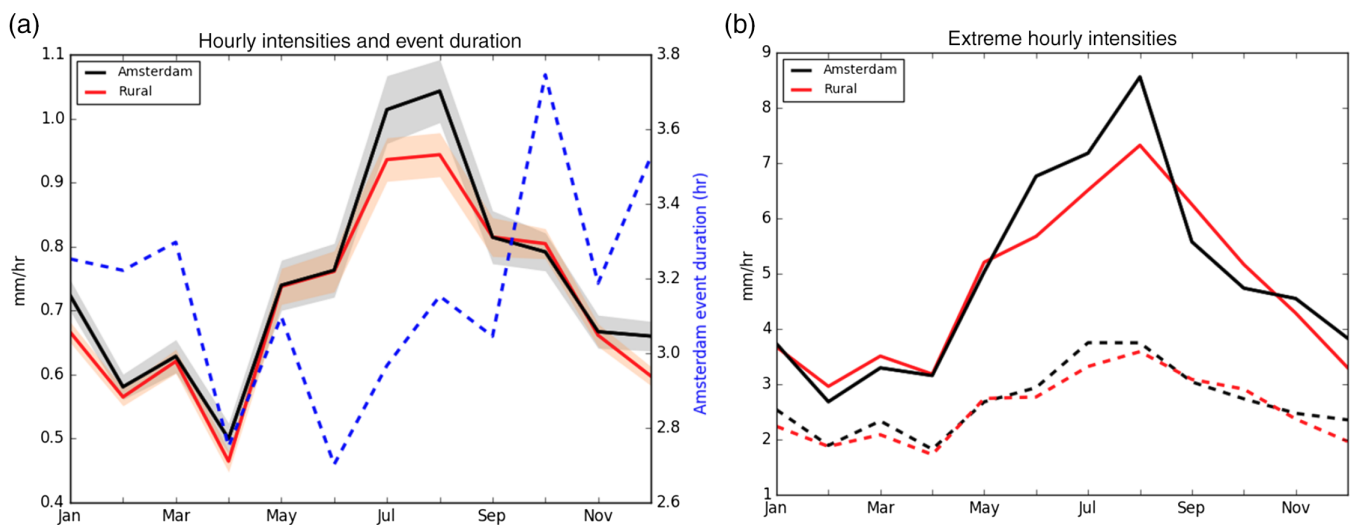

FIGURE 5 (a) Monthly averages of hourly precipitation intensities in mm/hr for rainy hours for the years 2008–2017. The Amsterdam data is in black and the averages of the two rural areas are in red. The shaded areas indicate the standard error of the mean for the monthly values in the 10 years of data. The blue dashed line shows the duration of the average monthly precipitation event in Amsterdam. In graph (b), the 99th percentile of the observed hourly precipitation intensities is represented as solid lines, and the 95th percentile is represented as dashed lines

5 | AMSTERDAM PRECIPITATION

5.1 | Annual cycle

The annual precipitation cycle of the city of Amsterdam averaged over the years 2008–2017 is shown in Figure 4. Precipitation is relatively constant during autumn, December and January. In February it drops gradually, until April which is the driest month (40 mm). Then in May it gradually increases, until August which is the wettest month (125 mm). The observed annual cycle is influenced by synoptic scale and local land-sea interactions. In autumn and

winter, the frequent passage of synoptic systems from the North Sea induces frequent large-scale precipitation of relatively low intensities and long durations. October has the longest-lasting precipitation events, about 3.8 hr on average per event (Figure 5a). In summer, most (heavy) rain is induced by local convection. The warm sea then renders adequate moisture to the air that is advected towards the relatively warm land, where it converges and produces convective precipitation of shorter duration and relatively higher intensities. Therefore, the shortest duration and the highest hourly intensities are observed in summer. The highest

monthly average (1 mm/hr) and heavy hourly intensities (8.5 mm/hr, the 99th percentile) are observed in July and August. The shortest events occur in June, about 2.7 hr on average. Overall, the driest season is spring, during which the lowest total precipitation amounts are observed as well as the lowest event frequency (about 25 events per month), a short event duration and relatively low average, heavy (95th percentile) and extreme (99th percentile) intensities (Figures 4 and 5). The precipitation in spring is influenced by the relatively low SST, which suppresses shower activity over areas close to the sea (Lenderink *et al.*, 2009).

The most intense precipitation events in terms of hourly intensities are observed mainly in the warm season, from May to September, with the maximum frequency of occurrence in July and August (Figure 6). For the event selection, the maximum area-averaged hourly intensity per day is taken into account. Selecting the 95th percentile threshold highlights the 125 heaviest hourly rain events for each of the three selected areas (Amsterdam and the two rural areas) over the 10 years of data. The 95th percentile is an appropriate threshold for drawing conclusions regarding the seasonal cycle of occurrence. As for higher percentiles (due to the low number of events) the noise levels are high and do not allow conclusions to be drawn. Primarily responsible for the hourly heavy and extreme summer rainfall events are the brief, intense convective storms that are also often related to frontal or cyclonic systems. The (fewer) winter hourly heavy events are usually related to frontal systems associated with

FIGURE 6 Histogram of the 125 most intense hourly rain events for each of the three selected areas in the years 2008–2017. The selected threshold is the 95th percentile of hourly intensity. The threshold for the 95th percentile in Amsterdam is 6.1 mm/hr, for the southern rural area it is 5.5 mm/hr, and for the northern rural area it is 5.3 mm/hr. The months are on the horizontal axis, and the normalized frequency of occurrence for each of the three selected areas is on the vertical axis

the frequent passing of cyclonic systems in the mid-latitudes (Catto and Pfahl, 2013).

5.2 | Weekly cycle

An analysis of the weekly precipitation cycle in Amsterdam for summer and winter at first shows a rather distinct pattern (Figure 7b). In summer, the total amount of precipitation on Tuesdays appears to be 7% higher than on Fridays, and in winter, the total amount on Tuesdays is found to be 6% higher than on Sundays. However, when further statistical tests are applied, those variations are proven insignificant. Following the method of Stjern (2011), the weekly cycle is compared to an arbitrary 5-day and a 9-day cycle. If the weekly pattern was related to anthropogenic activity, then the arbitrary *n*-day cycles would be expected to show relatively uniform precipitation amounts. To the contrary, Figure 7 shows that differences between days are approximately equally large for the week and the random *n*-day cycles. This indicates that the weekly cycle cannot be attributed to any anthropogenic cycle. Figure 7 indicates that the 9-day cycle shows precipitation differences of up to 8% between days, and the 5-day cycle, of up to 10% between days. As in Stjern (2011), a Kruskal–Wallis nonparametric test is also used to test the equality of population medians between the days of maximum differences. The test both for winter and summer resulted in large *p*-values ($>.05$), indicating that the observed weekly cycle in precipitation is not statistically significant.

Thus, no conclusions can be drawn regarding the influence of anthropogenic weekly heat emissions in Amsterdam and the consequent aerosol cycle on the atmospheric dynamics that could drive weekly periodicities of precipitation.

Relevant studies around the globe on weekly precipitation cycles have shown similarly conflicting results. In neighbouring Germany, for example, significant weekly precipitation cycles are seen in 15 years of observations (Bäumer and Vogel, 2007), but when the relevant patterns were further statistically investigated in the polluted Black Triangle (East Germany, Poland, and the Czech Republic), (Stjern, 2011) those distinct patterns are eventually found to be statistically insignificant.

5.3 | Diurnal cycle

Although the observed diurnal patterns of rain are rather noisy and the confidence intervals are relatively wide and sensitive to temporal and spatial changes, some overall conclusions can be drawn. The average annual diurnal cycle shows a double rain peak, one in the late night/early morning hours, and a second in the afternoon (Figure 8c). The seasonal variation of the diurnal cycle shows that this double
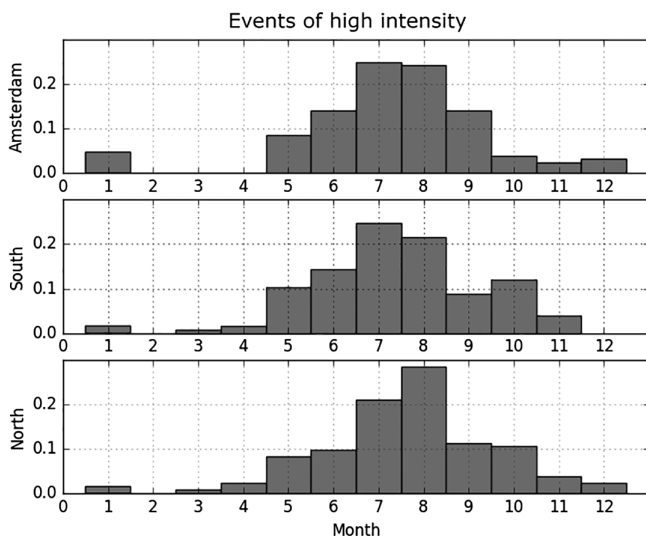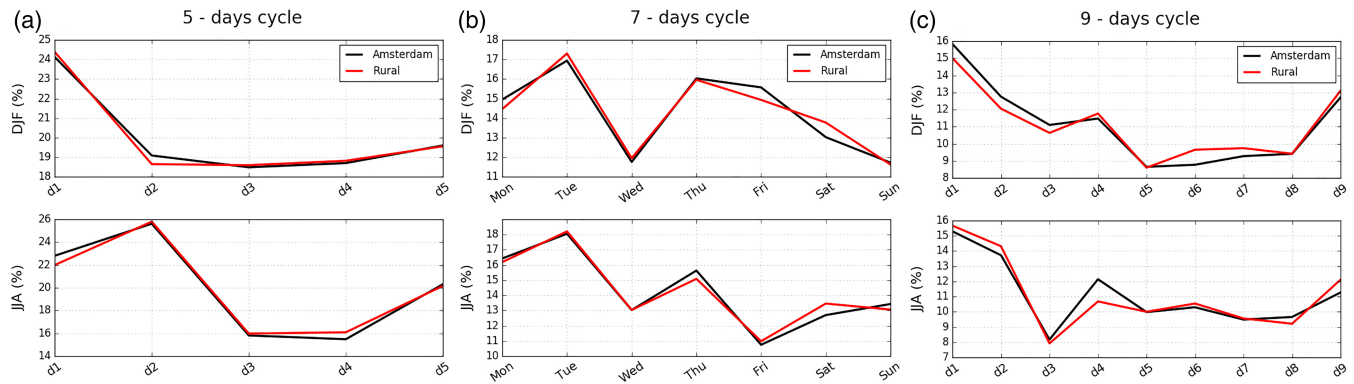
FIGURE 7 The percentage of total precipitation attributed to each day in (a) an arbitrary 5-day cycle, (b) a 7-day cycle, and (c) an arbitrary 9-day cycle. The upper panel shows the winter months, and the lower the summer months. The black line shows the data for Amsterdam, and the red line shows the rural data

peak appears primarily in the summer and secondarily in spring, although during spring, the intensities are considerably reduced (not shown). During the warm season, solar radiation plays an important role in the triggering of convection which often occurs late in the afternoon and plays a role in the formation of the afternoon peak in Figure 8b. The second peak in the early morning may be related to showers generated elsewhere that survive the night due to radiative cooling at the cloud top. In such a case, the cool air sinks, inducing turbulence and thereby maintaining the vertical motion. In winter (Figure 8a), a single moderate maximum is seen late in the afternoon and early in the evening.

No significant time preference is observed with regard to the occurrence of the maximum during a heavy or extreme rain event in the day (on days for which the maximum hourly areal average exceeds the 95th percentile). The time of the day at which this maximum took place is plotted as a frequency distribution in Figure 8d. The exact timing is quite sensitive to the percentile selection, season, and study area. In the study by Overeem *et al*. (2009b), which surveyed the entire country for the years 1998–2008, the diurnal cycle of the maximum rain showed a preference for the end of the afternoon, which was attributed to convection.

5.4 | Urban influence on Amsterdam precipitation

In order to assess the impact of the city of Amsterdam on precipitation, the preceding analysis is now discussed for the two rural areas north and south of Amsterdam (locations indicated in Figure 1a). The results are superimposed in the results figures.

This analysis shows that, throughout the year, the monthly urban rainfall is higher compared to that of the surrounding rural areas, with the largest urban–rural differences seen in July and August (up to 11% higher total

precipitation) and minimum differences in October (only 2% higher) (Figure 4). A bootstrapping technique based on resampling with replacement provides the 95% confidence intervals of the monthly precipitation. The urban–rural differences exceed the bootstrap confidence intervals, especially for the winter and summer months, indicating that the differences are statistically significant.

Those higher total precipitation amounts in Amsterdam compared to the rural areas in the summer can be explained by both a higher frequency of events (Figure 4b) and higher hourly (average and extreme) intensities (Figure 5), suggesting enhanced convective activity over the urban area. The most prominent discrepancies with respect to the occurrence of monthly precipitation events are seen in June, where it rains 32 times on average in the city, compared to only 24 times on average in the rural areas.

In winter, the observed higher total precipitation amounts in the city are caused by the higher average hourly precipitation intensities, and in January and February also by the higher number of precipitation events. Figure 5b, however, indicates that urbanization does not significantly influence the extreme hourly intensities of winter.

The higher urban total precipitation amounts in autumn and spring can mainly be explained by the higher frequency of occurrence of events compared to the rural areas (in April, May, October, and November), while the average and extreme hourly intensities are not considerably different in the urban and rural areas.

The duration of precipitation events is overall found to be insensitive to urbanization, as only small differences within the noise range are seen (plotting the rural durations is omitted for brevity). As a result, a sub-hourly investigation of the precipitation duration is suggested for future study, especially for the summer season, because convective events are usually of short duration and because the hourly data might not be sufficient for such an analysis.
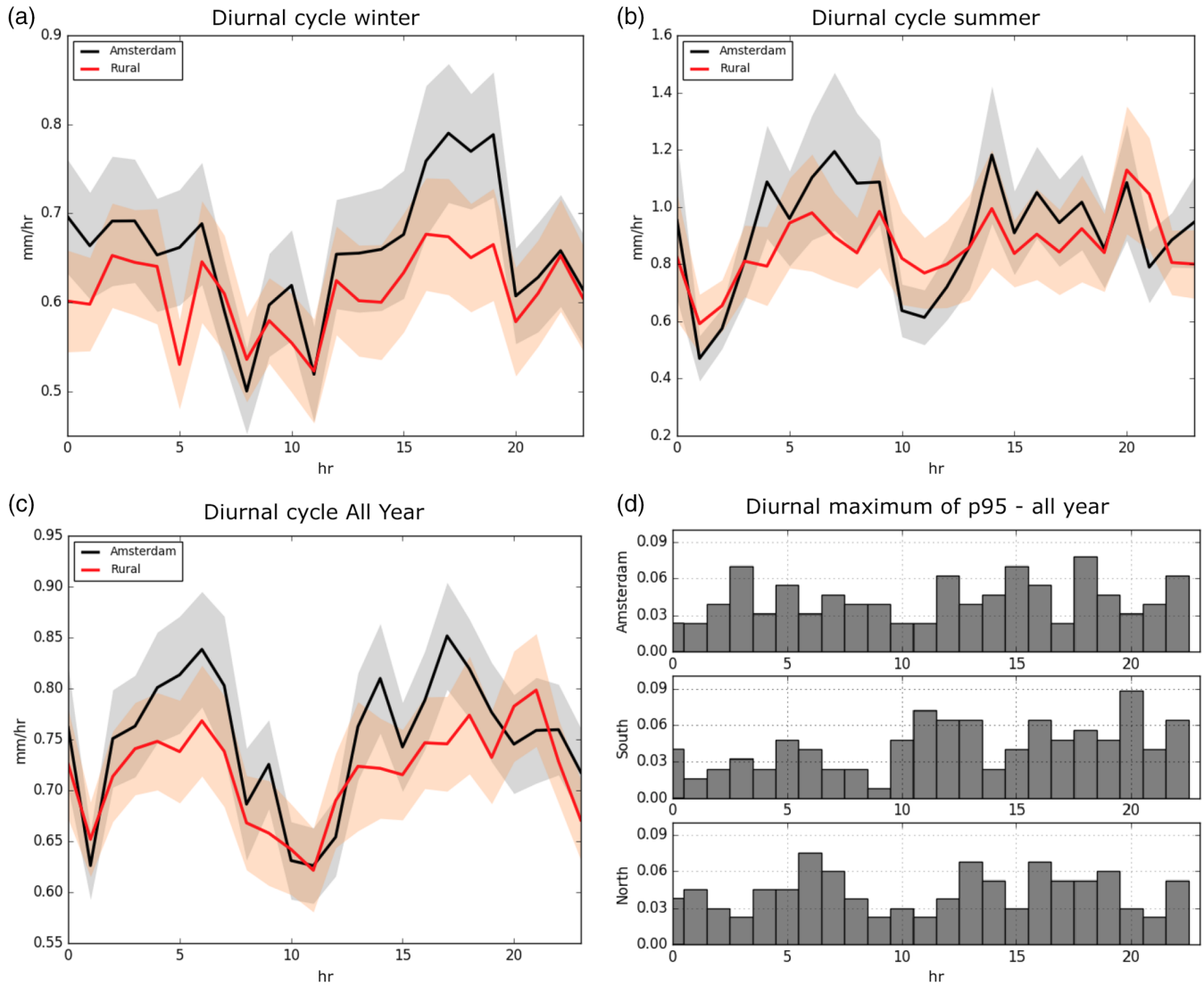
FIGURE 8 The observed diurnal cycle of rainfall in mm/hr in local time (UTC + 1) as the average intensity of rainy hours for the years 2008–2017 for Amsterdam (in black) and for the rural areas (in red). Graph (a) represents winter; (b), summer; and (c), annual values. The shaded areas indicate the standard error values. Chart (d) represents the frequency distribution of the time of the day when hourly events with intensity exceeding the 95th percentile occurred in the three study regions

The weekly cycles in the city and the rural areas show similar patterns, and for all seasons, the differences are small and insignificant (less than 1%), leading to the conclusion that no significant urban or rural weekly precipitation cycle occurs.

The urban and rural diurnal cycle patterns are similar (Figure 8), but the annual averaged diurnal cycle of Amsterdam has a more prominent cycle with a stronger double peak. The overlapping uncertainty bands, however, indicate that the differences are mostly not significant. A stronger evening peak occurs in the city during winter, and a stronger early morning peak during summer. The time of occurrence during the day of the maximum precipitation during heavy and extreme events (as seen in Figure 8d) does not allow for

any conclusion regarding a possible urbanization influence as no distinct pattern is seen in any of the three analysed areas.

6 | PRECIPITATION AND WIND DIRECTION

The origin and transport of the moisture for precipitation events can be analysed in terms of wind directions as an indicator of the trajectory of a given rain event (Eden *et al.*, 2018). The prevailing winds in the Netherlands are of westerly and southerly directions (Sluijter *et al.*, 2011) and are related to the prevailing synoptic westerly flow that

transports the storms induced by passing extratropical cyclones, as well as the storm track of the North Atlantic, which is formed mainly in the cold season. During the warm season, the westerly and southerly winds provide adequate moisture over the land to form convective precipitation.
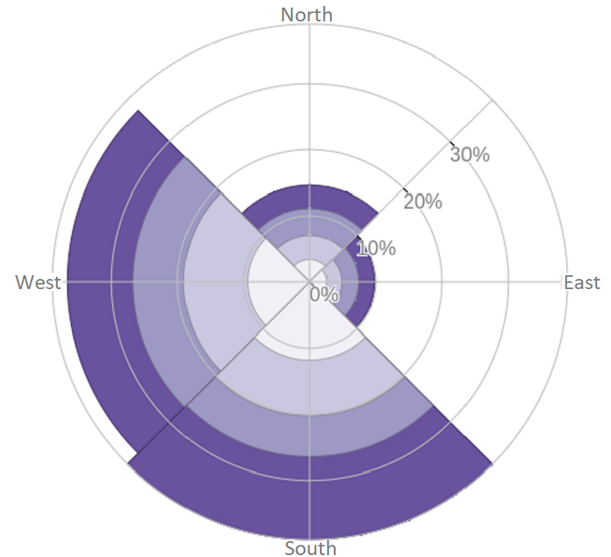
Wind roses of hourly surface wind directions are plotted in Figure 9 for dry and rainy hours and for extreme rain hours. The total amount of precipitation attributed to each wind direction is shown in Table 2. The dry hours account

for 85% of the total hours. The southerly and the westerly wind directions prevail both for dry and rainy hours. On an annual basis, 73% of the total precipitating water (Table 2) and 76% of the precipitating hours (Figure 9) can be attributed to westerly and southerly wind, which enhance precipitation as they transport moisture from the sea to the land. Both in frequency of occurrence (counted as total hours of precipitation) and in attributed precipitation amounts, westerlies and southerlies are equally distributed (about 38%
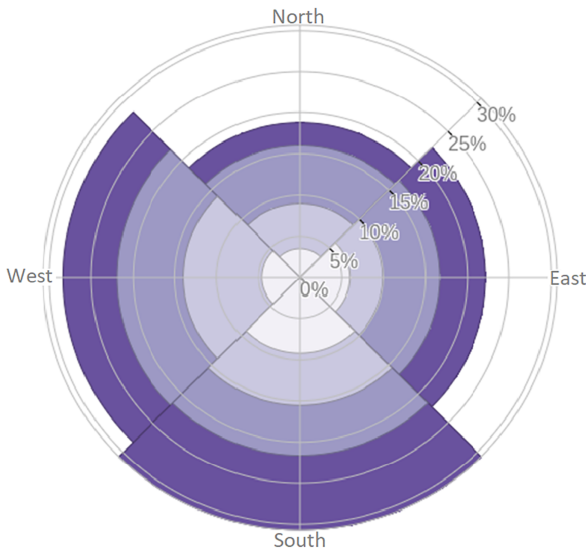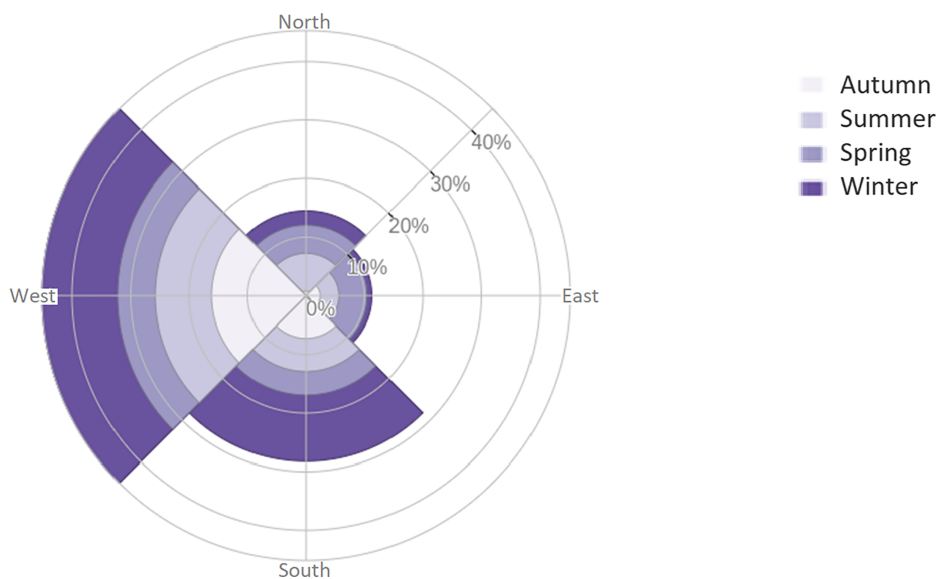

FIGURE 9 Wind roses indicating the frequency of each wind direction from observed hourly surface winds for the years 2008–2017. Each quarter represents a wind direction. The coloured concentric circles in each wind direction represent the four seasons. The width of each colour band indicates the frequency of occurrence of that direction and season. The noted percentages indicate the annual contribution of each wind direction. Wind rose (a) represents the wind directions during rainy (wet) hours; (b), during dry hours; and (c), during rainy hours with intensities exceeding the 99th percentile

	Total precipitation (mm)	West (%)	South (%)	North (%)	East (%)
Winter	254	31	50	10	9
Spring	158	36	30	17	17
Summer	313	40	30	18	12
Autumn	276	35	40	14	11
All year	1,001	35	38	15	12

TABLE 2 Cumulative precipitation amounts for the different wind directions in the four seasons

Notes: The column "Total Precipitation (mm)" gives the cumulative precipitation in mm per season and annually, averaged over the years 2008–2017. The following columns give the percentage of the relevant total precipitation associated with each wind direction per season and annually.

each). Nevertheless, some seasonal differences occur: southerlies prevail in winter, accounting for 50% of the total winter precipitation, while westerlies account for 30%. During summer, westerlies prevail, accounting for 40% of the total precipitation, and southerlies for 30%. The northerlies and easterlies account for precipitation amounts that range from 9 to 20% of the total precipitation and frequency of events in the different seasons. The northerlies account for 15% of the total annual precipitation, and the easterlies for 12%. Similarly to rainy hours, during dry hours southerly and westerly wind directions prevail overall, but the easterly and northerly directions occur more frequently compared to the rainy hours (a total 41% for the dry hours compared to 24% for the rainy hours), confirming that most of the moisture transport occurs over the sea as a result of the prevailing southerlies and westerlies.

In order to determine the wind directions associated with heavy and extreme precipitation, the threshold of the 95th percentile of hourly precipitation intensity was utilized to identify the 125 most intense events in the 10 years of data. The wind directions accounting for those events suggest that almost half of the heavy or extreme events are associated with westerly winds (Figure 9). The highest attribution of westerlies regarding heavy and extreme precipitation is seen in autumn, where westerlies account for 61% of the seasonal extremes. The contribution of southerlies to extreme precipitation is overall less strong compared to that of southerlies in all precipitation, as they account for 39% of all precipitating hours but only for 28% of the heavy or extreme rainfall hours. The impact of northerlies and easterlies on heavy precipitation for spring and summer is stronger, as they together account for 48% in spring and for 39% in summer.

7 | WTs AND PRECIPITATION

In this section, the observed precipitation over the city of Amsterdam is related to the Jenkinson and Collinson WT classification (JC, http://www.weathertypes.info) and the German Weather Service WT classification (DWD, Bissolli and Dittmann, 2001) to assess their ability to identify precipitation and extreme events. The dataset is divided into rainy and dry days and days of extreme rainfall. In Amsterdam, the number of rainy days is approximately equal to the number of dry days. In order to select the extreme events, the maximum hourly precipitation per day is selected, with those that exceed the 99th percentile threshold for summer and winter individually constituting of 11 winter and 11 summer extreme events.

Most classifications within the list of the WTs are observed for both rainy and dry days, and the frequency of occurrence is generally similar for rainy and dry days. The comparison of rainy days and precipitation amounts explained by each WT in the DWD classification shows that some WTs result in more intense precipitation and that others often do not contribute large amounts of water, especially in winter, even if they do appear (Figure 10). The latter are days of north-easterly or south-easterly winds with dry conditions, according to the DWD classification. However, this is not as clearly visible in the JC classification (Figure 11). Such long-lasting precipitation events that contribute small total amounts of water are related to the frequent passing of moderate intensity synoptic scale depressions that result in long-lasting stratiform winter drizzle. Both classifications agree that dry winter days are mostly of anti-cyclonic nature, either without winds or with winds from northerly or easterly directions. The rainy winter days in the JC classification are days of some westerly wind direction (38% of the rainy hours) or cyclonic conditions (20% of the rainy hours), or a combination of both (13% of the rainy hours). The rainy winter days in the DWD classification show a more variable pattern as the cyclonality and the wet/dry classification vary considerably, but with more consistent wind directions, as 60% of the rainy hours have some combination of wind directions that includes the southerly direction. It should be noted that a wet DWD day is not necessarily a rainy day, as their definitions differ (the definitions are given at Sections 3.2 and 3.3).

In the JC classification the 10 out of the 11 winter extreme events have either westerly winds or cyclonic circulation, or combinations thereof. In the DWD classification the 9 out of the 11 winter extreme events have south-
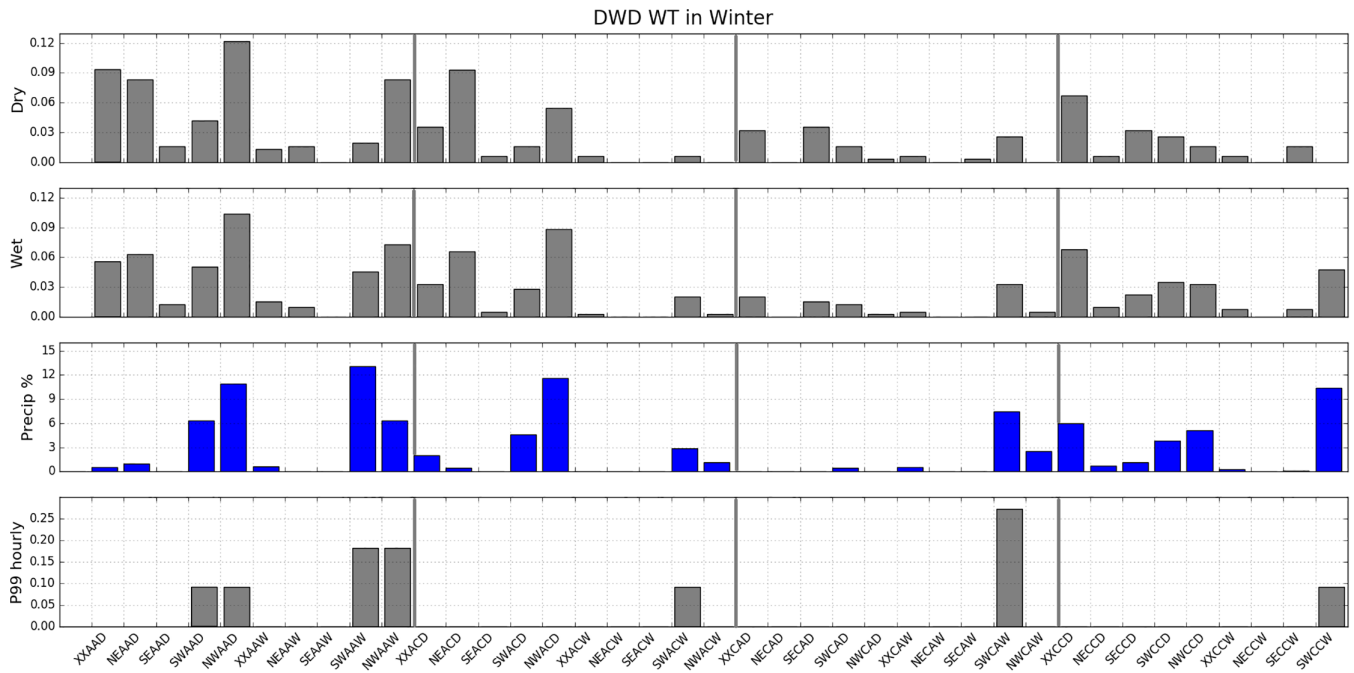
FIGURE 10 The frequency distribution of the German Weather Service weather types, for only dry days (top panel), only rainy days (second panel), the percentage of total precipitation explained by each weather type (third panel), and the frequency distribution of days with maximum hourly intensities exceeding the 99th percentile (bottom panel). Panels in grey indicate days explained by each weather type, and the panel in blue indicates the precipitation amount explained by each weather type. The legends in the *x*-axis are comprised of five letters: The first two letters indicate the wind directions (NE: northeast, SE: southeast, SW: southwest, NW: northwest, XX: no wind), the third letter indicates the cyclonality at 950 hPa; the fourth letter, the cyclonality at 500 hPa (C: cyclonic, A: anti-cyclonic); and the fifth letter, the humidity of the troposphere (W: wet, D: dry)

westerly winds and the rest north-westerly. The cyclonality in the DWD is less consistent. Extreme events associated with westerly winds are mainly caused by passing frontal systems, and extremes associated with cyclonic circulation are mainly of convective character. However, sometimes a system does not move fast and although the rain may be frontal, the system appears as cyclonic.

The rainy summer days in the JC classification are primarily dominated by cyclonic conditions (30% of the rainy hours) and secondarily by westerly winds and cyclonic westerly combinations (Figure 12), because most precipitation in Amsterdam in the summer has a convective character and because the passing of frontal systems is less frequent compared to the winter. The rainy summer days according to the DWD classification are dominated by south-westerly winds (60% of rainy days), mostly with a cyclonic component and a wet DWD classification (Figure 13). In both classifications, the amount of water attributed to each WT is comparable to the frequency of occurrence of each.

Five out of the 11 extreme summer events, according to the JC classification, are classified as cyclonic—a clear representation of strongly convective events. Seven out of those 11 events, according to the DWD classification, have south-westerly winds, are mainly classified as wet and have no preference for cyclonality. This finding is consistent with a

relevant recent study investigating the DWD patterns on summer extreme hourly precipitation in Hamburg (Weder *et al*., 2017), which showed a preference for south-westerly winds and wet conditions, with no particular preference in cyclonality, but also indicated events with north-westerly winds.

Table 3 lists the dates of the 11 extreme events and the WT classification for each. Although for each classification there are preferred patterns for the extremes, a comparison between the two classifications renders little agreement. One reason for this may be the distance between the centres of the two WTs, as the JC is the United Kingdom and the DWD is in Germany, which distance is relative to the average size of a synoptic system itself. This disagreement suggests that a future relevant study should investigate a WT classification that is centred over the Netherlands for improved precision. An evident correspondence between extreme precipitation and WTs is found, but in cases of local convective precipitation, the relation is weaker between such events and the dominant synoptic conditions.

8 | SUMMARY AND DISCUSSION

A considerable increase in cumulative precipitation and extreme precipitation intensity has been observed in the
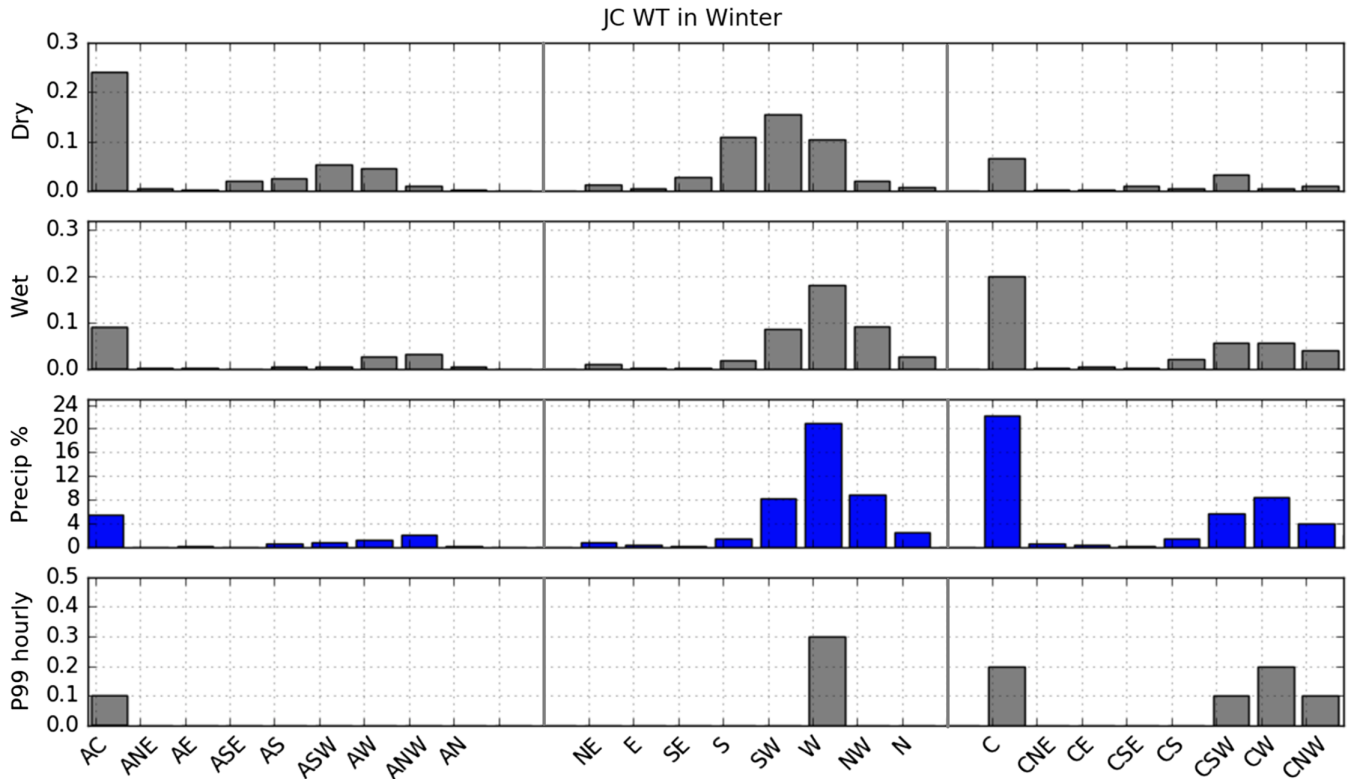
FIGURE 11 The frequency distribution of the Jenkinson and Collinson weather types during winter, similarly to Figure 10, for only dry days (top panel), only rainy days (second panel), the percentage of total precipitation explained by each weather type (third panel), and the frequency distribution of days with maximum hourly intensities exceeding the 99th percentile (bottom panel). Panels in grey indicate days explained by each weather type, and the panel in blue indicates the precipitation amount explained by each weather type. The legends are C: cyclonic and A: anti-cyclonic, and the wind directions are N: north, E: east, W: west, and S: south

Netherlands over the past decades (Buishand *et al.*, 2013). Concurrently, a rapid expansion of urbanization has changed the land use, thus altering parameters that can influence the formation, duration, and intensity of precipitation (Daniels *et al.*, 2016a). As precipitation in the Netherlands is projected to further increase due to climate change (Van den Hurk *et al.*, 2014) and as urbanization is continuously progressing, we need a deeper understanding of the current state of precipitation and of the parameters that influence it in order to improve future predictions and to contribute to the design of rain-proof cities. This analysis is a detailed spatial and temporal analysis of precipitation in and around the Dutch capital, Amsterdam. It assesses the observed influence of urbanization and evaluates how local wind and synoptic WTs relate to mean and extreme precipitation.

This analysis utilizes quality controlled Dutch weather radar observations at a spatial resolution of 1 km over a period of 10 years, from hourly to seasonal scales. The study first summarizes the precipitation accumulation patterns in the Netherlands. The observed average seasonal precipitation reveals a distinct urban influence, as statistically significantly higher precipitation accumulations are found over Dutch cities. This urban influence is strongest in winter and

over larger cities, with up to 14.2% enhanced precipitation, which is in line with the findings of Daniels *et al.* (2016a).

In the province of South Holland (location shown in Figure 1a), higher average seasonal precipitation values are observed than those that occurred in the rural areas in winter. This is caused by the warm sea at the beginning of the winter and the unstable conditions that trigger showers near the coast (Attema and Lenderink, 2014). At the same time, this region is known for its widespread greenhouses. The occurrences of extensive rainfall and the location of greenhouses coincide quite closely; thus, it can be hypothesized that the greenhouses might also play a role in the excessive precipitation. Most greenhouses in the area are warmed by burning natural gas locally during winter, thus emitting combustion heat and possibly increasing the local temperatures. In order to investigate such a hypothesis, further analysis is required, which is beyond the scope of the current work.

Amsterdam has a distinct annual cycle of monthly precipitation, with a minimum of 40 mm in April and a maximum of 125 mm in August, with the least frequent precipitation in spring and the most frequent in November. The duration of precipitation events is longest in winter and autumn, when large-scale precipitation is dominant, and shortest in summer
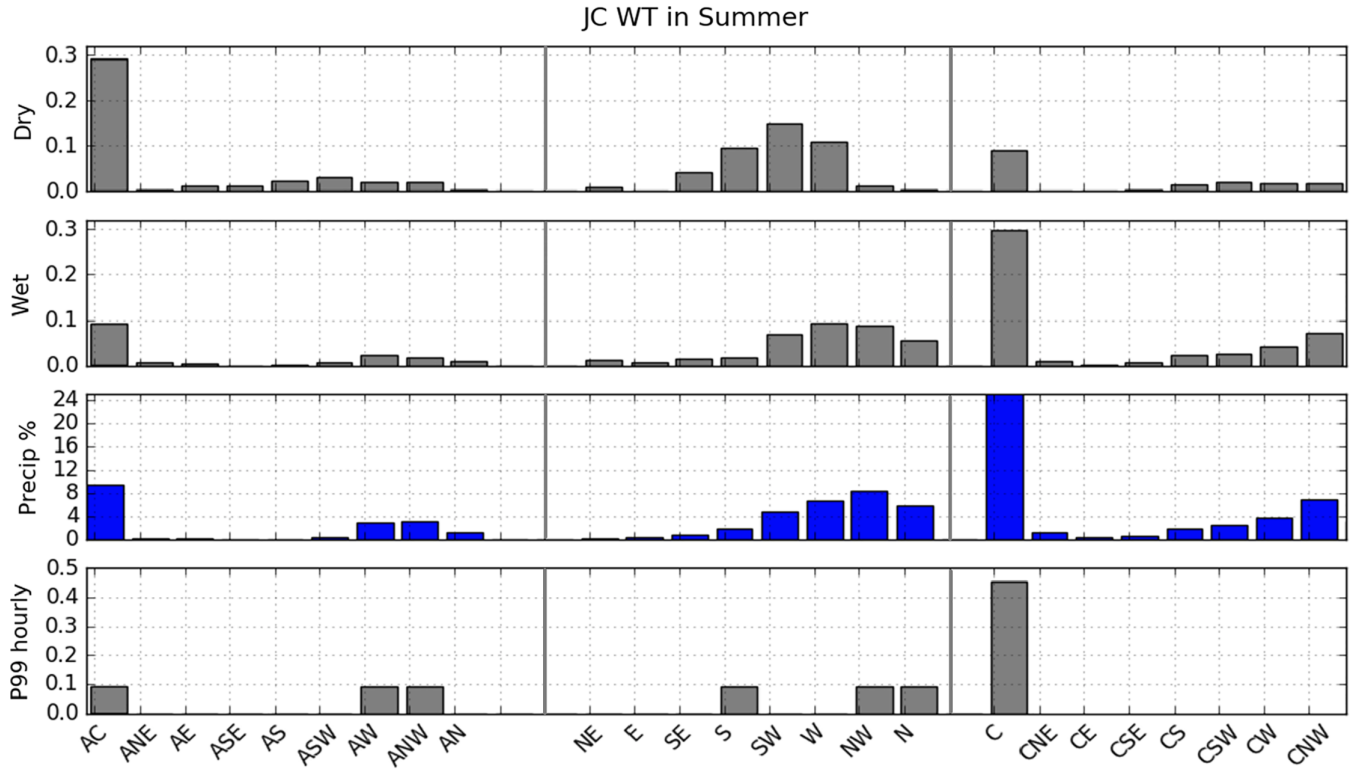
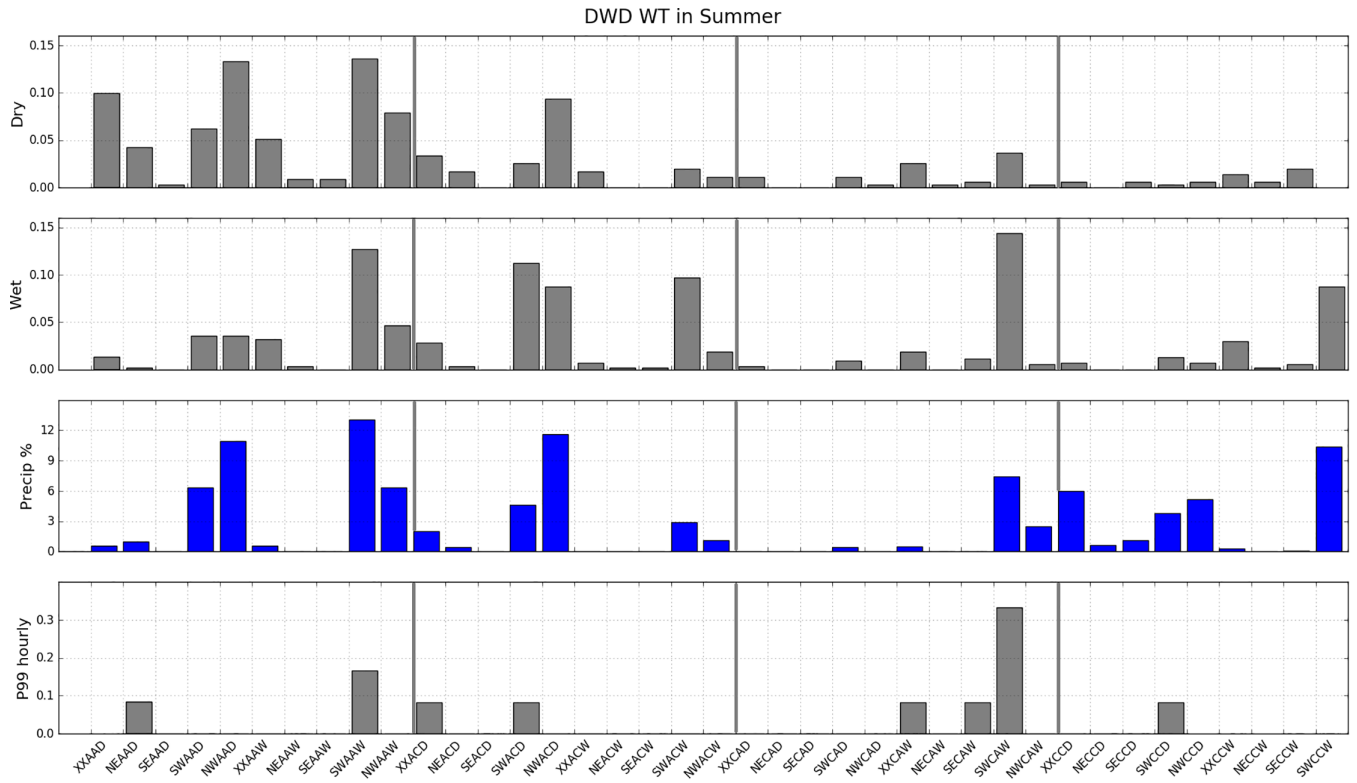**FIGURE 12** Same as Figure 11, but for summer days

FIGURE 13 Same as Figure 10, but for summer days

TABLE 3 The 11 most extreme precipitation events for winters and summers for the years 2008–2016

	Summer					Winter					
Date	Max (mm/hr)	Total (mm)	Duration (hr)	JC	DWD	Date	Max (mm/hr)	Total (mm)	Duration (hr)	JC	DWD
7/8/2008	12	19	5	C	SWCAW	11/1/2008	4	26	10	C	SWCAW
8/6/2010	10	13	4	C	SWCAW	22/1/2009	4	7	5	CSW	SWAAD
10/7/2010	12	24	4	S	XXCAW	10/12/2009	5	7	2	AC	SWCCW
23/8/2010	13	31	6	C	SWCAW	6/1/2011	5	16	8	CNW	SWCAW
14/7/2012	12	35	6	NW	SWACD	8/12/2011	5	7	4	CW	NWAAD
19/7/2012	12	14	2	N	SWCCD	1/1/2012	5	24	7	W	NWAAW
31/8/2012	10	25	4	AC	XXACD	3/1/2012	5	10	5	CW	NWAAW
11/7/2014	20	22	2	AW	NEAAD	8/1/2014	6	13	4	W	SWAAW
28/7/2014	21	64	7	ANW	SECAW	6/2/2014	4	11	10	C	SWACW
26/8/2015	11	22	3	C	SWAAW	7/1/2016	9	17	5	C	SWCAW
23/6/2016	10	38	8	C	SWAAW	30/1/2016	4	20	9	W	SWAAW

Note: The columns indicate the date of the event, the maximum hourly precipitation (as the average precipitation over Amsterdam at the peak hour), and the total precipitation during the event, the duration of the event, and the representative weather types according to the Jenkinson and Collinson and the German Weather Service classifications.

Abbreviations: DWD, Deutscher Wetterdienst; JC, Jenkinson and Collinson.

and spring, where convective precipitation is dominant. However, because precipitation events often are shorter than an hour, a duration analysis with sub-hourly data is recommended. Most intense hourly extremes occur from May to September, with a maximum frequency of occurrence in July and August, as a result of the frequent passing of intense short-term convective storms. The diurnal cycle of precipitation has a double peak in summer and a single peak in winter, with relatively high uncertainties. No significant diurnal cycle occurs during heavy and extreme hourly precipitation. A relevant study for the city of Hamburg showed a rather low signal of diurnal cycle, except for the summer season, when larger values were observed in the afternoon and early evening hours (Weder *et al.*, 2017).

This exploration of the differences in the precipitation between urban Amsterdam and two equal-sized rural areas north and south of the city indicates that urbanization does have an impact on precipitation. Observed monthly precipitation reveals a substantial and significant tendency of higher precipitation amounts in Amsterdam compared to the rural surroundings, with the largest differences seen in summer (up to an 11% increase) and in winter (up to 10%). These higher totals can be explained by a higher frequency of events in the city and by higher hourly mean intensities. In summer, extreme intensities are enhanced (up to 16% in August when considering the 99th percentile), while in winter no urban influence is observed in the hourly extremes. Although distinct weekly precipitation patterns for summer and winter can be found, they nonetheless fail to pass tests of significance, which is consistent with Stjern (2011).

These patterns are therefore attributed to natural variability. The urban diurnal precipitation cycle is somewhat more intense than the rural diurnal cycle, but the differences are mostly not significant.

Hourly wind data from the World Meteorological Organization (WMO) weather station closest to Amsterdam indicate that westerlies and southerlies account for about 75% of the total precipitation, as those directions promote moisture transport from the sea to the land. Heavy and extreme precipitation follow the same path, with most extreme events attributed to air masses of westerly or southerly directions with some seasonal variations. Long-term past observations (Cusack, 2013) and simulations of future weather with state-of-the-art numerical models indicate that the wind in the Netherlands experiences some decadal-scale variations, but no long-term trends or significant future changes (Van den Hurk *et al.*, 2014). However, CMIP5 model runs indicate that in the coming decades some intensification of westerly and south-westerly winds and a decline of northerly winds, which is compatible with a poleward shift of the storm track, could occur (De Winter *et al.*, 2013). Such changes may result in appreciable precipitation changes.

Finally, the precipitation in Amsterdam has been related to the JC and DWD WTs to assess their ability to identify precipitation and extreme events. Dry winter days are associated with anti-cyclonic circulation, with no winds, or with winds of northerly or easterly orientations. Rainy winter days are associated with westerly winds and cyclonic conditions. Rainy summer days are dominated by cyclonic conditions with westerly winds, according to the JC classification,

and with south-westerly winds, according to the DWD's WTs. The DWD classification identifies WTs that result in higher total precipitation amounts. In both classifications most extreme events show recurrent patterns, consisting of westerly or south-westerly winds or cyclonic circulation, but the agreement between the two methods is rather weak. The disagreements between the two classifications suggest the need to develop a classification that is centred over the Netherlands. The WT classification can to some extent be a valuable application for identifying rain and extreme rain events, although in the case of convective events, the local conditions tend to play a more important role.

To conclude, this work presents ample evidence that rainfall in Dutch cities is significantly larger than in their rural surroundings.

ACKNOWLEDGEMENTS

ORCID

Iris Manola https://orcid.org/0000-0003-2531-560X

REFERENCES

Andrade, C., Santos, J.A., Pinto, J.G. and Corte-Real, J. (2011) Large-scale atmospheric dynamics of the wet winter 2009–2010 and its impact on hydrology in Portugal. *Climate Research*, 46(1), 29–41.

Ashley, W.S., Bentley, M.L. and Stallins, J.A. (2012) Urban-induced thunderstorm modification in the Southeast United States. *Climatic Change*, 113(2), 481–498.

Attema, J.J. and Lenderink, G. (2014) The influence of the North Sea on coastal precipitation in The Netherlands in the present-day and future climate. *Climate Dynamics*, 42(1–2), 505–519.

Bárdossy, A. and Filiz, F. (2005) Identification of flood producing atmospheric circulation patterns. *Journal of Hydrology*, 313, 48–57.

Bäumer, D. and Vogel, B. (2007) An unexpected pattern of distinct weekly periodicities in climatological variables in Germany. *Geophysical Research Letters*, 34(3). https://doi.org/10.1029/2006gl028559.

Bell, T.L., Rosenfeld, D. and Kim, K.M. (2009) Weekly cycle of lightning: evidence of storm invigoration by pollution. *Geophysical Research Letters*, 36(23). https://doi.org/10.1029/2009GL040915.

Bissolli, P. and Dittmann, E. (2001) The objective weather types classification of the German Weather Service and its possibilities of application to environmental and meteorological investigations. *Meteorologische Zeitschrift*, 10, 253–260.

Brauer, C.C., Overeem, A., Leijnse, H. and Uijlenhoet, R. (2016) The effect of differences between rainfall measurement techniques on groundwater and discharge simulations in a lowland catchment. *Hydrological Processes*, 30, 3885–3900. https://doi.org/10.1002/hyp.10898.

Buishand, T.A., Jilderda, R. and Wijngaard J.B. (2009) *Regionale verschillen in extreme neerslag (in Dutch)*. KNMI, De Bilt. Report number: WR-2009-01. Available at: www.knmi.nl/bibliotheek/knmipubWR/WR2009-01.pdf

Buishand, T.A., De Martino, G., Spreeuw, J.N. and Brandsma, T. (2013) Homogeneity of precipitation series in The Netherlands and their trends in the past century. *International Journal of Climatology*, 33, 815–833.

Burt, T.P. and Ferranti, E.J.S. (2012) Changing patterns of heavy rainfall in upland areas: a case study from northern England. *International Journal of Climatology*, 32(4), 518–532.

Catto, J.L. and Pfahl, S. (2013) The importance of fronts for extreme precipitation. *Journal of Geophysical Research: Atmospheres*, 118 (19), 10,791–10,801.

Cerveny, R.S. and Balling, R.C., Jr. (1998) Weekly cycles of air pollutants, precipitation and tropical cyclones in the coastal NW Atlantic region. *Nature*, 394(6693), 561–563.

Cusack, S. (2013) A 101 year record of windstorms in The Netherlands. *Climatic Change*, 116(3–4), 693–704.

Daniels, E.E., Lenderink, G., Hutjes, R.W.A. and Holtslag, A.A.M. (2014) Spatial precipitation patterns and trends in The Netherlands during 1951–2009. *International Journal of Climatology*, 34(6), 1773–1784.

Daniels, E.E., Lenderink, G., Hutjes, R.W.A. and Holtslag, A.A.M. (2016a) Observed urban effects on precipitation along the Dutch West coast. *International Journal of Climatology*, 36(4), 2111–2119.

Daniels, E., Lenderink, G., Hutjes, R. and Holtslag, A.A.M. (2016b) Relative impacts of land use and climate change on summer precipitation in The Netherlands. *Hydrology and Earth System Sciences*, 20, 4129–4142.

De Winter, R.C., Sterl, A. and Ruessink, B.G. (2013) Wind extremes in the North Sea Basin under climate change: an ensemble study of 12 CMIP5 GCMs. *Journal of Geophysical Research: Atmospheres*, 118(4), 1601–1612.

Dou, J., Wang, Y., Bornstein, R. and Miao, S. (2015) Observed spatial characteristics of Beijing urban climate impacts on summer thunderstorms. *Journal of Applied Meteorology and Climatology*, 54(1), 94–105.

Eden, J.M., Kew, S.F., Bellprat, O., Lenderink, G., Manola, I., Omrani, H. and van Oldenborgh, G.J. (2018) Extreme precipitation in The Netherlands: an event attribution case study. *Weather and climate extremes*, 21, 90–101.

Forster, P.M.D.F. and Solomon, S. (2003) Observations of a "weekend effect" in diurnal temperature range. *Proceedings of the National Academy of Sciences of the United States of America*, 100(20), 11225–11230.

Golroudbary, V.R., Zeng, Y., Mannaerts, C.M. and Su, Z.B. (2017) Detecting the effect of urban land use on extreme precipitation in The Netherlands. *Weather and Climate Extremes*, 17, 36–46.

Gong, D.Y., Ho, C.H., Chen, D., Qian, Y., Choi, Y.S. and Kim, J. (2007) Weekly cycle of aerosol-meteorology interaction over China. *Journal of Geophysical Research: Atmospheres*, 112(D22). https://doi.org/10.1029/2007JD008888.

Givati, A. and Rosenfeld, D. (2004) Quantifying precipitation suppression due to air pollution. *Journal of Applied Meteorology*, 43(7), 1038–1056.

Goodess, C. (2000) *The construction of daily rainfall scenarios for Mediterranean sites using a circulation-type approach to downscaling*. Thesis, Norwich, University of East Anglia.

Han, J.Y. and Baik, J.J. (2008) A theoretical and numerical study of urban heat island-induced circulation and convection. *Journal of the Atmospheric Sciences*, 65, 1859–1877. https://doi.org/10.1175/2007jas2326.1.

Hazeu, G.W., Bregt, A.K., de Wit, A.J.W. and Clevers, J.G.P.W. (2011) A Dutch multi-date land use database: identification of real and methodological changes. *International Journal of Applied Earth Observation and Geoinformation*, 13, 682–689.

Horton, P., Obled, C. and Jaboyedoff, M. (2017) The analogue method for precipitation prediction: finding better analogue situations at a sub-daily time step. *Hydrology and Earth System Sciences*, 21(7), 3307–3323.

Jacobeit, J., Philipp, A. and Nonnenmacher, M. (2006) Atmospheric circulation dynamics linked with prominent discharge events in Central Europe. *Hydrological Sciences Journal*, 51(5), 946–965.

Jenkinson, A.F. and Collison, F.P. (1977). *An initial climatology of gales over the North Sea, Synoptic Climatology*. Branch Memorandum No. 62, Meteorological Office, Bracknell.

Junkermann, W., Vogel, B. and Sutton, M.A. (2011) The climate penalty for clean fossil fuel combustion. *Atmospheric Chemistry and Physics*, 11(24), 12917–12924.

Koks, E.E., Bočkarjova, M., Moel, H. and Aerts, J.C.J.H. (2015) Integrated direct and indirect flood risk modeling: development and sensitivity analysis. *Risk Analysis*, 35, 882–900. https://doi.org/10.1111/risa.12300.

Koopmans, S., Theeuwes, N.E., Steeneveld, G.J. and Holtslag, A.A.M. (2015) Modelling the influence of urbanization on the 20th century temperature record of weather station De Bilt (The Netherlands). *International Journal of Climatology*, 35(8), 1732–1748.

Köppen, W. and Geiger, R. (1928) *Klimate der Erde*. Gotha: Verlag Justus Perthes Wall-map 150cmx200cm.

Kron, W., Steuer, M., Löw, P. and Wirtz, A. (2012) How to deal properly with a natural catastrophe database-analysis of flood losses. *Natural Hazards and Earth System Sciences*, 12(3), 535–550.

Lenderink, G., Van Meijgaard, E. and Selten, F. (2009) Intense coastal rainfall in The Netherlands in response to high sea surface temperatures: analysis of the event of August 2006 from the perspective of a changing climate. *Climate Dynamics*, 32(1), 19–33.

Li, Z., Niu, F., Fan, J., Liu, Y., Rosenfeld, D. and Ding, Y. (2011) Long-term impacts of aerosols on the vertical development of clouds and precipitation. *Nature Geoscience*, 4(12), 888–894.

Manola, I., Hurk, B.V.D., Moel, H.D. and Aerts, J.C. (2018) Future extreme precipitation intensities based on a historic event. *Hydrology and Earth System Sciences*, 22(7), 3777–3788.

Niyogi, D., Lei, M., Kishtawal, C., Schmid, P. and Shepherd, M. (2017) Urbanization impacts on the summer heavy rainfall climatology over the eastern United States. *Earth Interactions*, 21(5), 1–17.

Obled, C., Bontron, G. and Garçon, R. (2002) Quantitative precipitation forecasts: a statistical adaptation of model outputs through an analogue sorting approach. *Atmospheric Research*, 63(3–4), 303–324.

Overeem, A., Holleman, I. and Buishand, A. (2009a) Derivation of a 10-year radar-based climatology of rainfall. *Journal of Applied Meteorology and Climatology*, 48(7), 1448–1463.

Overeem, A., Buishand, T.A. and Holleman, I. (2009b) Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar. *Water Resources Research*, 45(10). https://doi.org/10.1029/2009WR007869.

Parajka, J., Kohnová, S., Bálint, G., Barbuc, M., Borga, M., Claps, P., Cheval, S., Dumitrescu, A., Gaume, E., Hlavčová, K. and Merz, R. (2010) Seasonal characteristics of flood regimes across the Alpine–Carpathian range. *Journal of Hydrology*, 394(1–2), 78–89.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P. and Dubash, N.K. (2014) *Climate change, 2014*. Synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151). IPCC.

Petrow, T., Zimmer, J. and Merz, B. (2009) Changes in the flood hazard in Germany through changing frequency and persistence of circulation patterns. *Natural Hazards and Earth System Sciences*, 9(4), 1409–1423.

Queralt, S., Hernández, E., Barriopedro, D., Gallego, D., Ribera, P. and Casanova, C. (2009) North Atlantic Oscillation influence and weather types associated with winter total and extreme precipitation events in Spain. *Atmospheric Research*, 94(4), 675–683.

Raziei, T., Bordi, I., Santos, J.A. and Mofidi, A. (2013) Atmospheric circulation types and winter daily precipitation in Iran. *International Journal of Climatology*, 33(9), 2232–2246.

Rosenfeld, D. (2000) Suppression of rain and snow by urban and industrial air pollution. *Science*, 287(5459), 1793–1796.

Rosenfeld, D., Dai, J., Yu, X., Yao, Z., Xu, X., Yang, X. and Du, C. (2007) Inverse relations between amounts of air pollution and orographic precipitation. *Science*, 315(5817), 1396–1398.

Santos, M., Santos, J.A. and Fragoso, M. (2015) Historical damaging flood records for 1871–2011 in Northern Portugal and underlying atmospheric forcings. *Journal of Hydrology*, 530, 591–603.

Schmid, P.E. and Niyogi, D. (2013) Impact of city size on precipitation-modifying potential. *Geophysical Research Letters*, 40(19), 5263–5267.

Schmid, P.E. and Niyogi, D. (2017) Modeling Urban Precipitation Modification by Spatially Heterogeneous Aerosols. *Journal of Applied Meteorology and Climatology*, 56(8), 2141–2153.

Seto, K.C., Güneralp, B. and Hutyra, L.R. (2012) Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America*, 109(40), 16083–16088.

Shem, W. and Shepherd, M. (2009) On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. *Journal of Atmospheric Research*, 92, 172–179. https://doi.org/10.1016/j.atmosres.2008.09.013.

Shepherd, J.M., Pierce, H. and Negri, A.J. (2002) Rainfall modification by major urban areas: observations from spaceborne rain radar on the TRMM satellite. *Journal of Applied Meteorology*, 41(7), 689–701.

Simmonds, I. and Keay, K. (1997) Weekly cycle of meteorological variations in Melbourne and the role of pollution and anthropogenic heat release. *Atmospheric Environment*, 31(11), 1589–1603.

Sluijter, R., Leenaers, H. and Camarasa, M. (Eds.). (2011) *De Bosatlas van het klimaat*. Groningen, The Netherlands: Noordhoff Uitgevers.

Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., van Hove, L.W.A. and Holtslag, A.A.M. (2011) Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in The Netherlands. *Journal of Geophysical Research – Atmospheres*, 116, D20129. https://doi.org/10.1029/2011jd015988.

Stjern, C.W. (2011) Weekly cycles in precipitation and other meteorological variables in a polluted region of Europe. *Atmospheric Chemistry and Physics*, 11(9), 4095–4104.

Stocker, T. (Ed.) (2014) *Climate Change 2013: The Physical Science Basis*. Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Ter Maat, H.W., Moors, E.J., Hutjes, R.W.A., Holtslag, A.A.M. and Dolman, A.J. (2013) Exploring the impact of land cover and topography on rainfall maxima in The Netherlands. *Journal of Hydrometeorology*, 14, 524–542.

Tolika, K., Anagnostopoulou, C., Maheras, P. and Kutiel, H. (2007) Extreme precipitation related to circulation types for four case studies over the Eastern Mediterranean. *Advances in Geosciences*, 12, 87–93.

Trigo, R.M. and DaCamara, C.C. (2000) Circulation weather types and their influence on the precipitation regime in Portugal. *International Journal of Climatology*, 20(13), 1559–1581.

Van den Hurk, B., Siegmund, P. and Tank, A.K. (Eds.). (2014) *KNMI'14: Climate Change Scenarios for the 21st Century - A Netherlands Perspective*. De Bilt, Netherlands: KNMI.

Van Haren, R., van Oldenborgh, G.J., Lenderink, G., Collins, M. and Hazeleger, W. (2013) SST and circulation trend biases cause an underestimation of European precipitation trends. *Climate Dynamics*, 40, 1–20.

Van Oldenborgh, G.J., Drijfhout, S.S., van Ulden, A.P., Haarsma, R., Sterl, C., Severijns, A., Hazeleger, W. and Dijkstra, H.A. (2009) Western Europe is warming much faster than expected. *Climate of the Past*, 5, 1–12. https://doi.org/10.5194/cp-5-1-2009.

Van Oldenborgh, G.J. and Lenderink, G. (2014) Een eerste blik op de buien van maandag 28 juli 2014. *Meteorologica*, 3, 28–29.

Ward, P.J., Jongman, B., Weiland, F.S., Bouwman, A., van Beek, R., Bierkens, M.F.P., Ligtvoet, W. and Winsemius, H.C. (2013) Assessing flood risk at the global scale: model setup, results, and sensitivity. *Environmental Research Letters*, 8, 044019. https://doi.org/10.1088/1748-9326/8/4/044019.

Weder, C., Müller, G. and Brümmer, B. (2017) Precipitation extremes on time scales from minute to month measured at the Hamburg Weather Mast 1997-2014 and their relation to synoptic weather types. *Meteorologische Zeitschrift*, 26, 507–524.

Wilby, R.L. and Quinn, N.W. (2013) Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. *Journal of Hydrology*, 487, 109–121.

Yang, X., Li, Z., Liu, L., Zhou, L., Cribb, M. and Zhang, F. (2016) Distinct weekly cycles of thunderstorms and a potential connection with aerosol type in China. *Geophysical Research Letters*, 43, 8760–8768. https://doi.org/10.1002/2016GL070375.

Yang, P., Ren, G. and Yan, P. (2017) Evidence for a Strong Association of Short-Duration Intense Rainfall with Urbanization in the Beijing Urban Area. *Journal of Climate*, 30(15), 5851–5870.

Zhang, W., Villarini, G., Vecchi, G.A. and Smith, J.A. (2018) Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. *Nature*, 563(7731), 384–388.