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Detecting the effect of urban land use on extreme precipitation in the Netherlands

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A B S T R A C T

A notable increase in heavy precipitation has been observed over the Netherlands in recent decades. The aim of this study was to assess the influences of urban land use on these extreme precipitation patterns. Significant differences between an earlier multi-decadal period and a recent period were found in the Netherlands between 1961 and 2014. The significant changes in different indices indicate that severe precipitation events were not distributed homogeneously across the study area. The precipitation probability and distribution were assessed using the block maxima approach by comparing observations from urban and rural areas at different timescales. The possible effects of land use on extreme precipitation were assessed by quantifying the differences between urban and rural rain gauge stations according to the spatial gridding method. This study shows that urban land use may have affected the extreme precipitation patterns across the Netherlands. The data from all the categorized stations show that urban areas receive more intense extreme precipitation than do rural areas. Relative to other areas in the Netherlands, the urban areas in the western populated regions of the country exhibit prominent urban land use influences on the extreme precipitation patterns.

1. Introduction

Human life is more directly affected by precipitation than any other atmospheric phenomenon (Levizzani et al., 2002); thus, detecting changes in precipitation has become a critical research focus in recent decades (Hanel and Buishand, 2010). Extensive work has been dedicated to studying extreme precipitation events (Aguilar et al., 2009; Chen et al., 2012; Griffiths et al., 2005; Gutowski et al., 2010; Trenberth et al., 2007; van den Besselaar et al., 2012; Wang and Zhang, 2008; Westra et al., 2013; Willems, 2013a,b). Studies above have shown that precipitation and extreme events have increased at higher latitudes and that the intensity and frequency of extreme precipitation events have intensified. Physically, changes in the North Atlantic Oscillation (NAO) and the sea surface temperature (SST) are the major sources of precipitation changes in the Northern Hemisphere (Hurrell, 1995; Jones et al., 1997; Lenderink et al., 2009). In addition, several studies have shown that land use and topography can affect regional climates. Thus, extreme precipitation patterns can be influenced by the type of land use in high-latitude regions.

The Netherlands is located along the North Sea. Recent studies have revealed that the total precipitation and frequency of extreme events have increased over a large part of the Netherlands (Burauskaite-Harju et al., 2012; van Haren et al., 2013; Daniels et al., 2014; Rahimpour Golroudbary et al., 2016). Buishand et al. (2013) concluded that precipitation over the Netherlands increased by approximately 26% during the period from 1910 to 2013. Furthermore, Ter Maat et al. (2013) investigated the combined effects of forestation and topography on the maximum rainfall in the Netherlands and found that elevated forest areas (with a maximum elevation of 100 m) in the middle of the country received more precipitation than did the surrounding areas. Hurk et al. (2014) reported that the intensity of extreme precipitation in the western regions (including the most urbanised areas) was greater than that in the other regions of the Netherlands. The various physical and chemical processes (such as the Bowen ratio, heat storage capacity, and surface roughness) could be responsible for the effects of urban areas on precipitation (Oke, 1982; Shepherd, 2006; Mitra et al., 2012). Further studies also concluded that urbanisation effects on precipitation should be considered in the Netherlands (Daniels et al., 2015a,b).

This study investigates the variability in extreme daily precipitation and its spatial patterns across the Netherlands. The main objective is to

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analyse variations in extreme precipitation in three climatological periods and identify the likely discrepancy in extreme precipitation between urban and nonurban (rural) areas in the Netherlands. The link between the land use types and the monthly daily precipitation maxima was found by categorising stations in the Netherlands as urban or rural according to their local environmental characteristics (land use and surface features). This method is based on high-quality, historically observed precipitation data and the calculation of extreme precipitation indices and individual time series of the monthly daily precipitation maximum across the country.

In the following section, the precipitation data, precipitation indices, methods used in statistical analysis, and urban and rural stations are introduced. In section 3, the results and analysis of the trends in the observed indices are presented; the monthly amounts and trends during the different climatological periods are compared, and the regional differences in extreme precipitation are investigated. In section 4, the discussion is presented, and the conclusions are in section 5.

2. Materials and methods

2.1. Precipitation data

Long-term precipitation data from manual rain gauges in the Netherlands were quality controlled and validated (Buishand et al., 2013). These rain gauges reported daily precipitation (more details are provided at http://www.knmi.nl). The homogenised dataset was statistically tested and described by Buishand et al. (2013), and only a negligible difference in the detection of trends in extreme indices was observed between the homogenised dataset and the original quality-controlled dataset. A total of 231 rain gauges were used in this study, and the record length was 54 years (1961–2014). Complete data were available for 80% of the gauges, and missing data represented less than 1% of the data from the remaining gauges for this period. The missing data were replaced by values from ECAD (European Climate Assessment & Dataset) datasets (Klein Tank et al., 2002). The rain gauges have reasonable spatial coverage (with a spacing of approximately 10 km), and ordinary kriging was used to grid the precipitation data at a 1 km resolution (for a more detailed discussion, see Sluiter (2009, 2012, 2014)).

2.2. Definition of the precipitation indices

Extreme precipitation indices were defined to provide a true perspective of the observed changes based on the characteristics of the extreme events, including their frequency, amplitude, and persistence (Klein Tank et al., 2009). Extreme precipitation indices have been comprehensively described and classified into two groups (Zhang and Yang, 2004; Zhang et al., 2005; De Lima et al., 2010; Tian et al., 2011; Maragatham, 2012). The first group defines absolute thresholds and enumerates the number of days exceeding a certain absolute precipitation value, whereas the second group is based on percentile thresholds. The number of days exceeding a certain percentile threshold (representing the frequency of threshold crossing) is fixed for the World Meteorological Organization (WMO) base period (1961–1990). The specific indices used for this study are shown in Table 1. The details of the index definitions and calculations are described in Klein Tank et al. (2009). The extreme precipitation indices were calculated by using RClimDex (Zhang and Yang, 2004) software package in the R environment (R Foundation for Statistical Computing, Vienna, 2011).

2.3. Statistical analysis

This study investigated long-term time series data (period I: from year 1961–2014):

$$X_k = x_i,\ \ x_{i+1},\ \ \ldots,\ \ x_p \tag{1}$$

Table 1
Definition of the extreme indices for precipitation (P).

Indices	Indicator description (units)
Px1	Monthly maximum 1-day precipitation (mm)
Px5	Monthly maximum consecutive 5-day precipitation (mm)
Ptot	Annual total precipitation in wet days P ≥ 1 mm (mm)
SDII	Average daily precipitation amount on wet days (mm/day)
P10 mm	Annual count of days when P ≥ 10 mm (days)
P20 mm	Annual count of days when P ≥ 20 mm (days)
P30 mm	Annual count of days when P ≥ 30 mm (days)
CWD	Maximum number of consecutive wet days with P ≥ 1 mm (days)
P95Ptot	Annual total P (between 1961 and 2014) when P > 95th percentile of precipitation for the 1961–1990 period (%)
P99Ptot	Annual total P (between 1961 and 2014) when P > 99th percentile of precipitation for the 1961–1990 period (%)

where i = 1961, p = 2014, and k = 1, 2, …, 231. The time series of extreme values for each station (X_k) was divided into two multi-decadal periods as follows:

$$X_{k\_A} = x_i,\ \ x_{i+1},\ \ \ldots x_m \quad \text{and} \quad X_{k\_B} = x_{m+1},\ \ x_{m+2},\ \ \ldots x_p \tag{2}$$

where $m = \left(\frac{p+i}{2}\right)$, and the two multi-decadal periods in this study are defined as period II (from 1961 to 1987) and period III (from 1988 to 2014). The calculated value for m is rounded down to the nearest integer (i.e., 1987.5 rounded down to 1987).

The time series anomalies (D_{ki}) are calculated by considering the climatological average ($\overline{X}_k$) relative to the WMO base period (1961–1990) ($\overline{X}_{k\_WMO}$) for each station (k) as follows:

$$\overline{X}_k = \frac{\sum_{i=1961}^{2014}(x_i)}{54},\ \ \overline{X}_{k\_WMO} = \frac{\sum_{i=1961}^{1990}(x_i)}{30} \tag{3}$$

$$D_{ki} = \left(\frac{x_i - \overline{X}_{k\_WMO}}{\overline{X}_k}\right)*100 \tag{4}$$

where x_i is defined as in Equation (1) and PD_{ki} is the percentage anomaly for each station (k) and year (1961 ≤ i ≤ 2014). The overall percentage anomaly (PD_i) over the country (i.e. 231 stations) for each year i is defined as follows:

$$PD_i = \frac{\sum_{k=1}^{231} D_{ki}}{231} \tag{5}$$

The variation in precipitation could be observed visually or investigated using statistical methods (i.e., the hypothesis test). A broad range of parametric and non-parametric methods have been used to investigate trends in extreme precipitation in previous studies (Arnbjerg-Nielsen et al., 2013). In this study, the variations in precipitation observations were investigated using the Mann-Kendall test (Kendall, 1948; Mann, 1945) because of the non-Gaussian distributions of the observations.

In the Mann–Kendall test, the null and alternate hypotheses (H_0 and H_1) of the trend test are that no trend exists and that a monotonic trend exists in the time series, respectively. The Mann-Kendall statistical test is expressed as follows:

$$S = \sum_{i=1961}^{p-1} \sum_{j=i+1}^{p} sgn\ (X_j - X_i) \tag{6}$$

where X_j and X_i are sequential data. The term $sgn\ (X_j - X_i)$ is defined as follows: