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HLNUG
Für eine lebenswerte Zukunft
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
Institut für Geographie Giessen

BACHELOR THESIS

Heavy precipitation events in Central Germany on high temporal resolution and related atmospheric circulation in the period from 1961 until 2015

Starkregenereignisse in Mitteldeutschland auf der Basis zeitlich hochaufgelöster Daten und zugehörige atmosphärische Zirkulation in der Zeitspanne 1961 bis 2015

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Abbreviations

CDC	Climate Data Centre
DWD	German Weather Service
HPE	Heavy precipitation event
HPEs	Heavy precipitation events
GWL	Grosswetterlage (singular)
GWLs	Grosswetterlagen (plural)
GWLc	Grosswetterlagen-classification after HESS & BRESOWSKY
MJJAS	May, June, July, August, and September (here defined as summer season)
SVGc	SynopVis-Grosswetter-classification

1 Abstract

In order to reinforce the conclusion that heavy precipitation intensity has increased (much) more than monthly and annual precipitation, long-term station data in high temporal resolution (five-minute totals) from 19 stations located within Central Germany as well as daily precipitation totals of the same stations were used. They were evaluated for frequency and intensity trends for the time scales of five minutes, one hour, six hours, and one day in the period 1961–2015 for May to September. A significant increase in intensity for almost all stations was detected on the 5-min scale and no clear and significant trends for heavy precipitation events on 6-hour and daily scale. For the frequency of 5-min events an overall significant increasing trend was found especially during the last two decades and a more moderate increase for the events on 1-hourly and 6-hourly scale. The daily data has shown significant trends for individual stations. With the help of the comparison of the diurnal and seasonal cycles of mean and maximum precipitation of the periods 1961-1990 and 1991–2015 impacts of improvement in the measuring techniques in the 1990s were detected. The seasonal cycle of the frequency of heavy precipitation events on 5-min and daily scale furthermore led to the result that 5-min events are mainly driven by convection caused by higher solar radiation and higher air temperatures in mid-July. Daily events were assigned to be both convection and circulation driven. Finally the heavy precipitation events on 5-min and daily time scales were brought into context with weather patterns based on daily documented “Grosswetterlagen”. It was found out, that short and intense (convective) events were observed during atmospheric conditions with more eastern or southern inflow of warm air. High daily totals were connected to frontal rainfall in combination with mesoscale convective showers.

2 Introduction and Motivation

Increasing global air temperature and ocean surface temperature, acidification of the oceans, sea level rise, increasing greenhouse gas concentrations, and glaciers and ice melting are just a few of the changes attributed to Climate Change. But also the increase of extreme events such as heatwaves and droughts, causing forest- and wildfires, water scarcity, crop failures, health problems are raised into public awareness. This also applies to storms, floods, and last but not least heavy rain events. All these changes are closely linked to the term Climate Change and stand more or less in connection to changing temperature. These changes in our environment strongly affect humans and nature, and there is much agreement that human beings are exacerbating these changes (HARTMANN et al. 2013).

In recent years, extreme events in particular have become the focus of public attention, as people's direct involvement raises awareness of these phenomena. This includes the phenomenon of heavy precipitation. Heavy precipitation events (now abbreviated with HPEs, in singular HPE) on different time scales also have differentiated effects. While precipitation events with duration of over several hours or days led to flooding of rivers in the past, short-term but highly intensive rainfall locally very limited events led to high damage to infrastructure, agriculture, but also on people themselves. Since the prediction of these events is of high complexity or can only be made for a larger area many people are surprised by sudden heavy rain and lack the opportunity to prepare for such an event. If such heavy rainfall occurs over urban areas, which usually have a high degree of soil sealing, sewerage and rivers quickly reach their limits.

The 29th of May 2018 in Giessen serve as an adequate example. Here, the DWD had already given a warning of heavy thunderstorms and local heavy rain and hail in the morning. Between 18:30 and 20:00 UTC there was so much rainfall that the sewer system was unable to absorb these quantities of water. In further consequence several streets and many basements were under water (GIESSENER ALLGEMEINE 2018). The reason for the genesis of this event was a southeast cyclonal Grosswetterlage. Masses of hot air were over most of the continent and at the same time a mighty geopotential ridge was stretched to the North Cape, while flat troughs were formed above western and central Europe. This led to a labialization of the air layers and thus to heavy thunderstorms (DWD 2018a). In general Central Europe was affected by high temperatures and severe drought in summer 2018. The air masses, which mostly came from the northeast, brought dry air to Central Europe. These were caused by persistent high pressure systems from the UK to Scandinavia. As a result, low pressure areas were blocked from Central and Northern Europe. Through these dry air masses the formation of clouds was inhibited. This led to a higher solar radiation and usually caused the temperatures to rise unusually high. While in Northern Germany there was a pronounced drought, the high temperatures in the south and west were punctually accompanied by thunderstorms, HPEs and local flood events (MEINERT & SCHUBE 2018).

Examinations of changes in temperature and precipitation are already in abundance for this area. However, research on precipitation is mostly based on daily totals, while for the investigation of HPEs a much higher temporal resolution is desirable (e.g. BECKER et al. 2016). Those events are suspected to increase to a greater extent than the high daily totals that are associated with front passes and convection (e.g. LENDERINK & VAN MEIJGAARD 2008).

The latest IPCC report (AR5 - 2013) agrees with the conclusion of AR4 that HPEs increased disproportionally compared to changes in average precipitation amounts between 1951 and 2003 over many mid-latitude regions, also in areas, where a reduction in annual total precipitation was observed (HARTMANN et al. 2013). Many previous studies confirm this hypothesis on different regional and temporal scales (e.g. BARBERO et al. 2017, FORMAYER & FRITZ 2017, NISSEN & ULBRICH 2017, and FISCHER & KNUTTI 2016). To precise this hypothesis the following thesis compares results of previous studies on precipitation variability and trends during the 20th and the beginning of the 21th century with own results derived through the analysis of German station data. Therefore, the 99th percentile of daily maximum precipitation on five-minute, hourly and six-hourly scale, as well as daily totals were used to identify trends in the intensity of HPEs in summer season (May to September) from 1961 to 2015. The exceeding of predefined threshold values was also examined for all time scales in order to carry out a trend analysis. Additionally, the seasonal and diurnal cycle of the absolute maxima of five-minute precipitation data for the periods 1961–1990 and 1991–2015 were compared as well as the seasonal cycle of the frequency of HPEs on five-minute and daily scale. In order to show that HPEs of short duration are connected to warm temperatures the related atmospheric circulation based on the daily documented Grosswetterlagen was investigated.

Based on the calculations the following research questions should be answered:

1. Which trends appear in high-intensity precipitation events, comparing temporal high-resolution data (5 min, 1 h, 6 h) with daily precipitation data in Central Germany in the period 1961 to 2015?
2. How reliable are those trends considering instrumental changes in the time series?
3. How does atmospheric circulation impact the occurrence of high-intensity precipitation events, comparing precipitation data with five-minute and daily time scales?

In order to answer these questions it is necessary to understand the processes that force heavy precipitation and the relation to temperature or atmospheric circulation. Section 2.1 to 2.6 gives an insight into it, while section 2.7 contains a brief description of the project “KLIMPRAX Starkregen”, in which framework this thesis is written. In the section Data (3) the area of investigation (3.1), precipitation measurement history, technique, sources of error, and the origin of the data (3.2) are introduced. Furthermore the history, the definition, and the origin of the atmospheric circulation data given by the “Grosswetterlagen” (3.3) are presented. After demonstrating the Methods of the selection of the stations (4.1), the definition of the term HPEs on different time scales (4.2), the tendency tests used in the study (4.3) and an overview on the process of data analysis (4.4), the Results are presented. There trends in intensity (5.1.1) and frequency (5.1.2) as well as the seasonal cycle (5.2) and diurnal cycle (5.3) are shown. In another step the connection of HPEs and atmospheric circulation is shown (5.4). In section 6 these results are discussed in order to answer the research questions, identify gaps within the work, discuss the benefit of it and compare these results to the results of previous studies. Finally, in the Conclusion (section 7) the results are summarized and it is shown whether the research questions are answered to an adequate degree. Also an outlook on further needed research of HPEs on short time scales is given.

2.1 Scientific history of Climate Change and precipitation

Since the science of Climate Change has become a field of interest in the 1980s many new questions about the changing character of Earth’s Climate have occurred. One of the main aspects in Climate Change research is the changing character of precipitation. TRENBERTH et al. (2003) investigated this parameter in terms of intensity, frequency and duration with both observation and model data. They detected significant changes and concluded that these aspects have not been analysed to an adequate degree (TRENBERTH et al. 2003). The investigation of annual or seasonal average precipitation is of high interest, but in terms of Climate Change it is indispensable to have a detailed focus on HPEs and their frequency and intensity (LENDERINK & VAN MEIIJGAARD 2008). Therefore, HPEs have a special position in the IPCC-reports. The Odra River Flood 1997, the Elbe River Flood 2002, records of precipitation totals including flooding in the Alps in summer 2005 (KUNZ et al. 2009), and the “flood of the century” in Central Europe in May and June 2013 imply an increasing trend in HPEs. Although these drastic events are associated with heavy precipitation, they are more likely to be attributed to stratiform rainfall accompanied by convective showers and therefore precipitation events with high daily totals (e.g. LENDERINK & VAN MEIJGAARD 2008). In the present study, however, the term “heavy precipitation event” is defined for different time scales on the basis of five-minute data. A more differentiated definition will be given in section 4.2. While there is low confidence for most continents that HPEs are increasing in frequency and intensity because of insufficient data, North American and

European network show a reliable increase in the frequency of these events. HARTMANN et al. (2013) found a disproportional increasing trend in intensity and frequency of heavy precipitation events compared to average changes in the time span 1951 to 2003. Hence, precipitation is a parameter with high spatial variability caused by latitudinal, longitudinal, topographic, land-sea dependent differences, atmospheric circulation, and more, the contemplation of small-scale areas is essential for adaption (e.g. BRASSEUR et al. 2017). In general, over land and north of 30 °N an upward trend (especially for North America and Europe) in all seasons and a decreasing precipitation trend for the tropics has been detected (HARTMANN et al. 2013).

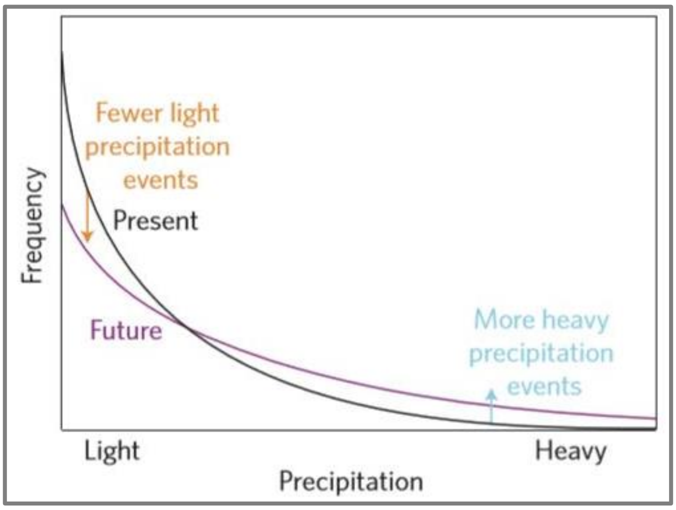

Figure 1: Heavy rainfall intensification in theory. Schematic rainfall distribution, by FISCHER AND KNUTTI 2016.

The intensification of heavy precipitation was predicted by theory and models in the 1980s and has been confirmed by observational data (FISCHER & KNUTTI 2016). FISCHER & KNUTTI therefore confirmed the assumption that heavy precipitation behaves different than annual precipitation totals to a warming atmosphere. As a consequence (and this is commonly agreed in the IPCC) HPEs are expected to become more frequent in future climate while light precipitation events are expected to become less frequent (illustrated in Figure 1). FISCHER & KNUTTI (2016) used European observation (EOBS) daily data from 1951 to 2013 to proof the hypothesis of higher frequency of HPEs. For this purpose they have shown that intense HPE frequency increased to a higher extent than less intense precipitation events comparing the periods 1951–1980 and 1981–2013.

2.2 Connection of heavy precipitation and changing air temperature

The physical connection between increasing frequency and intensity of HPEs and increasing temperature was subject of many previous studies (e.g. TRENBERTH et al. 2003, ALLAN & SODEN 2008, and WESTRA et al. 2013). In the late 20th century FOWLER & HENNESSY (1995), HENNESSY (1997), FREI et al. (1998), and TRENBERTH (1999) pointed out the influence of greenhouse gas emissions and temperature increase on the upward trend of HPEs. Their studies were based on daily data and a few of the pioneers for later research on this aspect of Climate Change. More recent studies verify the assumptions of these scientists. O'GORMAN AND SCHNEIDER (2009) concluded that daily precipitation extremes in mid-to-high latitudes often scale with the Clausius-Clapeyron rating, which states that in a warmer atmosphere the potential that more moisture is held is higher. This relation of increasing moisture-holding capacity and increasing temperature is approximately 7 % per °C (e.g. BERG & HAERTER 2013). Assuming a constant relative humidity in future water vapour in the atmosphere would increase to that Clausius-Clapeyron scaling (e.g. LENDERINK & VAN MEIJGAARD 2010 and BECKER et al. 2016). Particularly for convective precipitation (showers or thunderstorms), an intensification of the cloud-forming and precipitation-forming processes is assumed due to the higher air temperature (on the ground). The high variability of the different influencing factors of precipitation (atmospheric circulation, convection, and cloud physics) is important and leads to regional differences (BERG & HAERTER 2013). To make matters worse, it is precisely heavy precipitation, as defined in the following work, which is usually of very small-scale extent and therefore underestimated in the analysis of station data. The problem of the shortness of the time series with radar measurements, which cannot yet provide a climatologically reliable statement regarding the heavy rainfall development, should therefore be pointed out (WINTERRATH et al. 2017).

2.3 Heavy precipitation events on different time scales

Most studies investigating HPEs during the last decades used daily data. But to verify the hypothesis that extreme rainfall intensity and frequency increased in a higher extent on shorter time scales than (multi-) daily time scales it is essential to analyse sub-daily data on hourly or even shorter time scales (e.g. HARDWICK JONES et al. 2010). Due to rare data such studies are limited in regional and numerical extent the shorter the time scales (TRENBERTH 2011).

LENDERINK & VAN MEIJGAARD (2008) investigated hourly precipitation extremes in the context of Climate Change. They found a dependency twice the Clausius-Clapeyron relation at temperatures above 12 °C (daily average) for hourly precipitation extremes for De Bilt – Netherlands. Their results indicated that hourly extreme precipitation events had increased stronger in intensity than daily extreme precipitation events (LENDERINK & VAN MEIJGAARD 2008). On the basis of hourly western European station data LENDERINK & VAN MEIJGAARD (2010) figured out an intensification of precipitation double than the approximately 7 % per degree of warming given by the Clausius-Clapeyron relation at surface temperatures above 10 °C. They concluded that this could be explained by latent heat release in HPEs. BARBERO et al. (2017) analyzed hourly data from 1950 to 2011 for the United States. They came to the result that limited spatial extent of extreme events and the measurement interval truncation problem caused a more shallow increase of intensity of hourly extreme precipitation than extremes on daily time scales. In this particular study daily extremes followed an average percentage change per degree of warming of 6.9 % (Clausius-Clapeyron rate).

Relating to the research in sub-daily heavy precipitation HARDWICK JONES et al. (2010) investigated – as a continuation of LENDERINK & VAN MEIJGAARD (2008) its relationship to surface temperature and relative humidity for Australian observation data. They traced an agreement with the Clausius-Clapeyron rate for temperatures between 20 and 26 °C and precipitation events up to 30 minutes in duration and a negative scaling at higher temperatures. They concluded moisture availability as the main reason for heavy precipitation at higher temperatures. In another study UTSUMI et al. (2011) verified that sub-hourly (ten minute) heavy precipitation intensification went hand-in-hand with increasing surface temperatures for Japan, while on daily time scale an upward trend was not clearly observable. Crucial for this apparent opposite was a decrease in the duration and not in the intensity of precipitation events, which is fundamental for the adaption to HPEs.

For the analysis of sub-hourly heavy-precipitation events for Central Europe the studies of MÜLLER & PFISTER (2011) and FIENER et al. (2013) were pioneering. Both studies used precipitation data with one minute resolution for the Emscher-Lippe catchment area in Western Germany. MÜLLER & PFISTER (2011) demonstrated that erosion relevant rainstorm events increased in number since the 1940s especially during summer season (July to September). They filtered out events with duration from one to 30 minutes and demonstrated that events with exceedance of threshold values from 0.3 mm per minute and 20 mm per hour increased in frequency especially in the last 35 years of the investigated time span. The work of FIENER et al. (2013) has shown an increase in frequency and magnitude of erosive events in summer (April to November). For the time span 1937 to 2007 they detected a slight significant increasing erosivity of 4 % per decade and even 21 % for the time span 1972 to 2007. However, MÜLLER & PFISTER (2011) already drew attention to the high potential for error in high-resolution measurement series and that an interpretation of the results must therefore be made with reservations.

2.4 Convection

Besides fronts, which cause stratiform precipitation events with high spatial and temporal extent but with less intensity from hours to multiple days, there are convective rainfall events. These high intensive convective events are more local and of less duration from minutes to multiple hours and triggered by a vertical labialization of air masses (HOY & HÜBENER 2018). YE et al. (2017) investigated the relationship of convective and stratiform precipitation types with temperature change for Russia. They detected – in agreement with the Clausius-Clapeyron relation – a general increasing intensity of precipitation of 7 % per °C, but for convective precipitation events an increasing intensity of 18 % per °C. Thus, the temperature increase was attended by a decrease of stratiform and an increase in convective precipitation events. BERG & HAERTER (2011) attributed the increase in heavy precipitation on short time scales to the increase in convective precipitation. They analysed German station data in five-minute resolution, temperature and synoptic circumstances, identifying convective and stratiform cloud formations. Their results revealed a higher sensitivity of convective (higher than Clausius-Clapeyron rate) than stratiform (approximately Clausius-Clapeyron rate) precipitation with increasing temperature. They also pointed out the special annual and diurnal cycle of precipitation for German inland and coastal stations. They detected a midsummer maximum in the annual cycle and a main maximum in the afternoon and linked these results with convective processes (BERG & HAERTER 2011).

2.5 Heavy precipitation events in Germany

Regarding trends in frequency and intensity of HPEs, some studies have been conducted for Germany. In most cases daily data was used, which is partly available in Germany since the beginning of the 20th century. By analyzing daily precipitation data for eleven stations (in the period 1901-2000) and 54 stations (period 1941–2000) GRIESER & BECK (2002) found an increase in heavy precipitation days especially in winter. The trends for the summer months turned out to be less strong. The result was made for the increase in heavy precipitation, but higher percentage changes were observed, resulting in a higher intensity of HPEs. KREIENKAMP et al. (in DWD 2016) detected an increase in the days of heavy rainfall in spring, autumn and winter in the period 1951–2006. However, no such increase was detected for summer. A reliable statement for heavy precipitation short time scales could not be made. Although radar data is only available for the past 16 years, an increase in short-term heavy rain events was noted. But, due to the shortness of the period under consideration, this is not reliable from a climatological point of view and may be triggered by short-term and medium-term variations (WINTERRATH et al. 2017). In their analysis of data documented for more than 50 years spatially heterogeneous trends were identified.

The atmospheric conditions of the severe drought in northern Germany and heavy precipitation in Central and Southern Germany in mid to late May 2018 were studied by IMBERY et al. (2018). They identified subtropical air masses as drivers of constant thunderstorms and HPEs, which repeatedly led to flash floods. In fact during this time the atmospheric circulation was mostly shaped by southern or eastern air mass advection (DWD 2018a).

In the KOSTRA-DWD 2010 project[1], the phenomenon of heavy precipitation has already been investigated for the entire federal territory. This and several previous publications identified trends in the recurrence time and frequency of HPEs of different time scales (5 minutes to 72 hours) in the period 1951 to 2010 for the months of May to September. This was done on the basis of five-minute precipitation data for individual stations and transferred to regions without long-term precipitation registrations by using

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[1] KOSTRA: Koordinierte Starkniederschlagsregionalisierung und –auswertung

appropriate regionalization methods (MALITZ & ERTEL 2015). MALITZ et al. (2011) dealt with the frequency, recurrence and intensity of HPEs in Germany from 1901 to 2000. They detected no consistent trend in intensity for the summer heavy rainfall with high daily totals. However, a significant increase in the frequency of HPEs in the summer months was diagnosed for 16 of the 83 stations (more than 19 % of the stations). An insignificant increase was calculated for 42 stations, an insignificant decrease for 23 stations, and a significant decrease for two stations. Thus, MALITZ et al. (2011) identified an increase in the frequency of HPEs on a daily basis. In general, an increasing frequency of heavy precipitation was found for various regions of Germany.

Regarding the investigation of HPEs in Germany, PETROW et al. (2007), PETROW et al. (2009) and PETROW & MERZ (2009) gave some important results. PETROW & MERZ (2009) indicated with the help of runoff measurements that there was no consistent increase in the frequency and intensity of flooding events from the mid-20th century, as widely disseminated in the media. However, they pointed out that for most regions such an increase was observed mainly in winter, but in summer mostly a slightly increasing trend. PETROW et al. (2009) justified increasing frequency of winter flooding with increasing frequency and duration of certain circulation patterns. For summer, no uniform result could be found. PETROW et al. (2007) investigated the circulation patterns that are more likely to cause flooding. They pointed out that, especially in winter, the number of floods had increased, while in the summer lower frequencies had been observed, but with considerably higher intensity.

2.6 Heavy precipitation and atmospheric circulation

It is obvious that warm temperatures which force HPEs and water vapour content strongly depend on the inflow direction of the air masses. The connection of HPEs and their related atmospheric circulation has been subject in some earlier studies. The often used 29 “Grosswetterlagen” (GWLs) will be introduced in section 3.3. While HOY et al. (2013) investigated the impact of these large-scale circulation types on European precipitation, more local studies focused on e.g. Poland (DEGIRMENDZIC et al. 2004, LUPIKASZA 2009 and TWARDOSZ et al. 2011) and Hohenpeißenberg in Germany (FRICKE 2002). FRICKE (2002) used long term precipitation data of the station Hohenpeißenberg at the foothills of the Alps in southern Bavaria. He demonstrated an increasing frequency of circulation types driving HPEs as well as increasing frequency of days with more than 30 millimetres precipitation totals.

One aim of the present study was to clarify the occurrence of HPEs on five-minute and daily scale in context to circulation patterns. Therefore the original classification of the GWL (GWLc) and the automated objective Grosswetterlagen classification (SVGc) were used (see section 3.3 for an introduction).

2.7 Project “KLIMPRAX Starkregen”

HPEs influence different regions in the world more or less. Germany is affected by these events as well. In the face of this the HLNUG (Hessian Agency for Nature Conservation, Environment and Geology, in German: Hessisches Landesamt für Naturschutz, Umwelt und Geologie) located in Wiesbaden deals with HPEs in the project “KLIMPRAX Starkregen”[2]. Its major function is the support of municipalities concerning impacts of anthropogenic Climate Change for example convective, i.e. HPEs with high intensity in the short term. These mainly occur in summer months and are usually unexpected because of high complexity of prediction. Little warning time and therefore insufficient preparation often leads to large damages through arousing flash floods. Not only the occurrence of these events forces its negative influence on the society, but also human soil sealing enlarge the impacts (e.g. flooded infrastructure and through this triggered pollution of water bodies). Another aspect concerning HPEs and its frequency and intensity is its influence on rural environments, where HPEs have influence on agriculture, mainly through erosion (HLNUG 2018a).

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[2] Project in cooperation with the DWD (German Weather Service, in German: Deutscher Wetterdienst), HMUKLV (Hessian Ministry of the Environment, Climate Protection, Agriculture and Consumer Protection, in German: Hessisches Ministerium für Umwelt, Klimaschutz, Landwirtschaft und Verbraucherschutz), HMdIS (Hessian Ministry of the Interior and Sports, in German: Hessisches Ministerium des Inneren und für Sport), HST (Hessian Cities Council, in German: Hessischer Städtetag), and the HSGB (Hessian Association of Towns and Municipalities, in German: Hessischer Städte- und Gemeindebund).

3 Data

3.1 Area of investigation

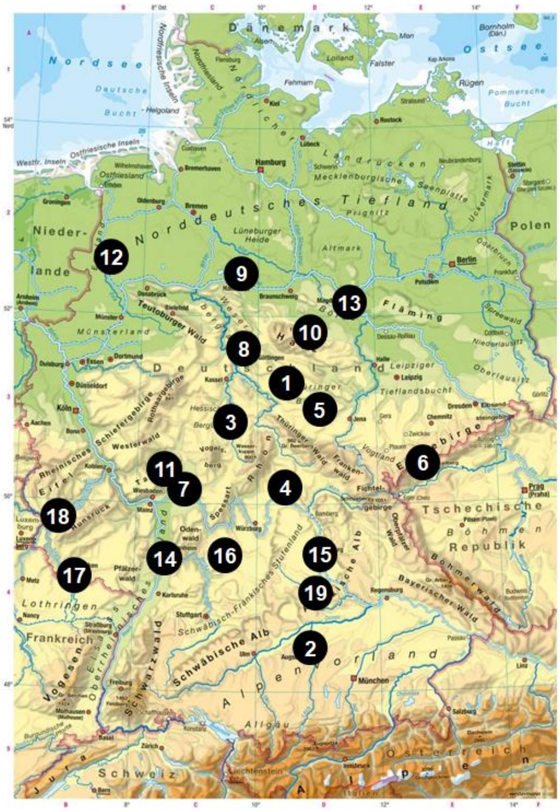


Figure 2: Location of the analysed stations, from DIERCKE 2018.

Map ID	Station name	Altitude a. s. l. in m
1	Artern	164
2	Augsburg	461
3	Bad Hersfeld	272
4	Bad Kissingen	282
5	Erfurt	316
6	Fichtelberg	1213
7	Frankfurt	100
8	Göttingen	167
9	Hannover	55
10	Harzgerode	404
11	Kleiner Feldberg	826
12	Lingen	22
13	Magdeburg	76
14	Mannheim	96
15	Nürnberg	314
16	Oehringen	276
17	Saarbrücken	320
18	Trier	265
19	Weissenburg	439

Table 1: Map IDs, locations and altitudes of the stations.

The area of investigation comprises Central-Western Germany and is characterized by a number of different low mountain ranges. In the North the investigation area is bordered by the North German Lowlands and in the East by Ore Mountains, Fichtel Mountains and the Upper Palatinate Forest in south eastern Germany. In the South the area is bordered by the alpine foreland and in the West by the Black Forest, the Eifel and the Hunsrück region which are located at the French and Benelux national borders (DIERCKE 2018). Namely it includes three Hessian (Bad-Hersfeld, Frankfurt and Kleiner Feldberg), four Bavarian (Augsburg, Bad Kissingen, Nuremberg and Weissenburg), and two stations in Baden-Wuerttemberg (Mannheim and Oehringen). Only one station is used for the Saarland (Saarbrücken), Rhineland-Palatinate (Trier) and Saxony (Fichtelberg). Also two stations in Thuringia (Artern and Erfurt-Weimar), two in Saxony-Anhalt (Harzgerode and Magdeburg), and three stations in Lower Saxony (Goettingen, Hannover, and Lingen) were used. Unfortunately, no stations with suitable data could be found for North Rhine-Westphalia.

In the following all stations are called by their German names, which are partly already abbreviated (e.g. Frankfurt am Main – Flughafen = Frankfurt).

Climatic conditions

In Central Europe precipitation occurs almost exclusively during northerly or westerly wind. This causes a blocking effect at the German low mountain ranges and the Alps which results in higher precipitation totals (HÄCKEL 2012). In general the uplift of air during overflow of mountainous regions has a cooling effect. So contained moisture condenses to raindrops and cause rainfall. Therefore higher values for mountainous regions and windward sides of mountains and lower values for lee-ward sides are expected. Additionally, the insolation also plays an important role in precipitation genesis. In summer the relatively early sunrise and more intensive insolation causes earlier and more frequent convection. This in turn causes the formation of thunderclouds (HLNUG 2018b). Due to this phenomenon, the mountains and the German low mountain ranges literally model themselves out of the maps of annual rainfall totals. Worth mentioning is that coasts, in this case the North Sea coast, also have an effect on precipitation totals. Due to a slowdown of the wind by topography, vegetation and cultivation, precipitation totals are higher than over the North Sea and the North German lowlands (HÄCKEL 2012).

The seasonal distribution of precipitation in Germany has two maxima (winter and summer) and two minima (spring and autumn). The more pronounced maximum occurs in summer and the secondary in winter. Overall, the annual cycle is more balanced in coastal areas than in the mid-mountain ranges, the Alpine foothills and the Alps. Comparing summer and winter the precipitation totals in Northern Germany summer totals exceed winter totals by 10 %. Towards the south, the summers are increasingly rainier in relation to the winters (HÄCKEL 2012).

Precipitation records

Worldwide precipitation records were, as to be assumed on the basis of the previous lines, observed close to mountainous regions. In Cherrapunji (Eastern India) annual sum (26461 mm in August 1860 to July 1861) and monthly sum (9300 mm in July 1861) are the highest values. On three-daily scale the record was observed on the island La Reunion in the Indian Ocean in February 2007 (3929 mm). Record value on daily scale originates from the same place from March 1952 (1870 mm) (SCHÖNWIESE 2013). Precipitation records in Germany are far lower than worldwide records. These are listed in Table 2.

Temporal resolution	German Record	Date/Year	Location
Annual	3503.1 mm	1970	Balderschwang/Allgäu
Monthly	777 mm	May 1933 and July 1954	Oberreute/Lindau and Stein/Rosenheim
24 hours	312 mm	August 2002	Zinnwald/Eastern Erzgebirge
8 minutes	126 mm	May 1920	Füssen/Allgäu

Table 2: German precipitation records on annual, monthly, daily, and eight-minute scale; own illustration, values from SCHÖNWIESE 2013.

3.2 Precipitation

3.2.1 Historical overview

Precipitation is one of the parameters with the longest history of measurement. 5000 years ago first reports indicate a use of techniques in China, around Christ birth in India and Israel and 1533 in Chile. First European measurements were conducted 1677 in Lancashire, England. The longest continuous collection of data originates from London since 1697. A network collecting international precipitation data was founded by Elector Karl Theodor from Bavaria and Palatinate in 1780, consisting of 39 stations from Massachusetts (USA) to Ural and from Greenland over Scandinavia to Italy. In the year 1985 4500 stations measuring precipitation in Germany existed (HÄCKEL 2012).

Currently the DWD operates at approximately 1900 German stations. Spatially high resolved daily data are available for the last 60 years, with partially higher resolution in earlier decades than more current. The longest period of continuous data collection for daily precipitation totals originates from Aachen since 1844 (BRASSEUR et al. 2017).

3.2.2 Measurement of precipitation

In general precipitation is given in millimetres and embraces totals for time spans like a year, a month, a day, etc. During the last decades some different techniques of measurement have been used. For this study are the classical Hellmann gauge (Hellmann-Niederschlagsmesser), the precipitation recorder according to Hellmann (Hellmann-Niederschlagsschreiber) and the precipitation sensor NG 200 which are volume measuring instruments are of importance. Newer measuring technology relies on the determination of the precipitation height by means of the weight. These are the precipitation sensor with tilting balance (Ombrometer) and the precipitation sensor Pluvio-Ott. These gained importance in the 1990s (DWD 2015).

In the following the different measuring techniques are just shortly summarized. The Hellmann gauge uses a circular collecting area of 200 cm² with funnel to ensure collection of the water in a measuring tank. For a meaningful daily value of precipitation total, an employee of the measuring station removes this measuring tank each day at the same time. For a higher temporal resolution of precipitation data, the Hellmann precipitation recorder was developed. It collects the precipitation water similar to the Hellmann gauge on an area of 200 cm². However, the precipitation level is automatically recorded using a quill that rises or falls with the water level on a writing drum. The more modern precipitation sensors as the precipitation rocker, which is also referred to as an Ombrometer, has a collecting area of 200 cm². In its process standardized modulated drops are counted by a photoelectric barrier and inserted in a funnel. In the further course, the drops reach a tilting balance. This tilts to a capacity of 0.1 mm and empties. This technique allows a measurement in the minute range.

The Pluvio-Ott also corresponds to a large extent to the design of the Hellmann gauge. Here, however, the falling precipitation is detected by determining the weight in the collecting tank and recorded directly in digital form with a resolution of 0.01 mm.

3.2.3 Data quality and sources of error

Measurement errors regarding precipitation are distinctive compared to temperature and pressure. Precipitations high degree of temporal and spatial variability and influence of environments are still complicating the prevention and identification of errors (SCHÖNWIESE 2013). To minimize errors originating from the measurement instrument some constructions are used to prevent errors induced by wind, evaporation, spraying loss, etc. (HÄCKEL 2012). However a complete prevention from errors is not possible and induced by orography, movement of stations and wind. In general it is assumed that even under most favourable terms measuring precision is about +/- 10 % (SCHÖNWIESE 2013). Hence for the analysis of station data it is essential to review metadata of the stations containing relocations, technical changes, changes in environments etc. These factors limit the analysis to stations with non-significant changes.

3.2.4 Origin of the data

The DWD offers a widespread collection full of climate data for free public use. This includes precipitation data on different time scales taken at 1900 stations in Germany. Beneath available multi annual, annual, monthly, daily and hourly scale, sub daily scales are in progress and can be obtained via the CDC (Climate Data Centre) portal on the website of the DWD (DWD 2018b). The data for this study consists of 19 stations with long term summer half year (May to September - MJJAS) rainfall data (including the years 1961 to 2015) in high resolution (five minutes). For detailed criteria for the selection of stations see section 4.1.

3.3 Daily “Grosswetterlagen”

3.3.1 Historical overview and definition

The “Grosswetterlagen” (now abbreviated with GWLs; in singular GWL) are used to classify Central Europe weather since the beginning of the 20th century. Hence weather depends on upper air flow these first attempts were limited (BOTT 2016). BAUR et al. (1944) were the first who established a catalogue for 21 European Grosswetterlagen from 1881 to 1939. These were defined by the average pressure of at least Europe during a time span of at least three days with (partly) constant weather situation. They were characterized by the location of driving pressure systems and the drift of frontal zones. A daily classification of the GWLs (GWLc) of Europe from 1881 to 1950 was published by HESS & BREZOWSKY (1952). Their definition of the GWLs included surface pressure fields as well as mid-tropospheric flow (JAMES 2007). Multiple revisions by HESS & BREZOWSKY (1969 and 1977) and continuations by GERSTENGARBE & WERNER (1993, 1999 and 2005) followed during the next decades (BOTT 2016). The most current update of the European GWLc was provided by WERNER & GERSTENGABE (2010) and describes 29 different GWLs (BOTT 2016) which are summarized in Table 3 (after HOY et al. 2013).

Grosswetterlage (GWL)	Abbrev.	Inflow
Anticyclonic Westerly	WA	W
Cyclonic Westerly	WZ	
South-Shifted Westerly	WS	
Westerly, Block Eastern Europe	WW	
Anticyclonic South-Westerly	SWA	SW
Cyclonic South-Westerly	SWZ	
Anticyclonic North-Westerly	NWA	NW
Cyclonic North-Westerly	NWZ	
High over Central Europe	HM	–
Zonal Ridge across Central Europe	BM	
Low (Cut-Off) over Central Europe	TM	
Anticyclonic Northerly	NA	N
Cyclonic Northerly	NZ	
Icelandic High, Ridge Central Europe	HNA	
Icelandic High, Trough Central Europe	HNZ	
High over the British Isles	HB	
Trough over Central Europe	TRM	
Anticyclonic North-Easterly	NEA	NE
Cyclonic North-Easterly	NEZ	
Scandinavian High, Ridge Central Europe	HFA	E
Scandinavian High, Trough Central Europe	HFZ	
High Scandinavian-Iceland, Ridge	HNFA	
High Scandinavian-Iceland, Trough	HNFZ	
Anticyclonic South-Easterly	SEA	SE
Cyclonic South-Easterly	SEZ	
Anticyclonic Southerly	SA	S
Cyclonic Southerly	SZ	
Low over the British Isles	TB	
Trough over Western Europe	TRW	

Table 3: Grosswetterlagen (GWLs) with inflow directions; own illustration, with information from WERNER & GERSTENGABE (2010).

From the manually (original) to an automated version

This GWLc is a subjective classification by an experienced meteorologist of the DWD using surface pressure and geopotential height of the 500 hPa. Paul James developed an automated version of the classification (“SynopVis-Grosswetterklassifikation” – short: SVGc). It considers geopotential heights at 500 hPa, air temperature fields at 850 hPa geopotential height, predictable water and mean sea-level pressure (HOY et al. 2013). Therefore the high quality and high resolution ECMWF ERA 40 re-analysis dataset provided by UPPSALA et al.

(2005) including September 1957 to August 2002 was used (JAMES 2007). As shown in section 5.4 both classifications differ in their distribution of the individual GWL.

3.3.2 Origin of the data

The used data for the daily GWLc until 2009 originate from WERNER & GERSTENGABE (2010) and is supplemented by data from 2010 to 2015 from monthly publications of the German Weather Service DWD (2010, 2011, 2012, 2013, 2014, 2015). The data for the SVGc could be ordered by personal contact (JAMES 2017).

4 Methods

For the processing and the analysis of the data and the visualisations of the results Microsoft Excel has been used.

4.1 Criterions for the data

In this study five-minute precipitation totals of 19 stations are used in order to investigate summer (MJJAS) precipitation. For this purpose first of all metadata of all Central German stations were reviewed. Only stations with non-significant shifts in location and measurement techniques as well as stations with as less as possible data gaps during the seasons and years of interest were used for the analysis. Following criterions were established:

Criterion 1: Only Central German stations (max. 200 km around Hessian borders)

Criterion 2: No significant shifts in location and environment

For the analysis of trends, it is desirable to have as long as possible time series with as constant as possible technical and local conditions. In order to exclude those stations, which fulfilled the first criterion of limitation to a maximum of 200 km distance to the Hessian border, but have too strong changes of the locations, the stations had to be examined for relocations. With the help of the metadata for each station obtained by personal contact, but also available via the CDC (DWD 2018b) it was possible to get an overview over relocations of the stations in longitude, latitude and altitude. The exact external influences in the landscape are unfortunately not preserved in the metadata. However, it can be assumed that relocation is important, especially at height. The maximum displacement of a station of this work in altitude was found for Bad-Hersfeld, which was moved at the end of 1994 by about 60 meters upwards. According to HLNUG (2018c), climatological statements based on the measured data of this station are only conditionally possible. A table with the changes in latitude, longitude and altitude can be found in the appendix. This table also provides an overview of the changes in measuring instruments, which have already been briefly explained in section 3.2.2.

Criterion 3: As little as possible data gaps in extended summer season (MJJAS)

The selection on the basis of this criterion was by far the most difficult criterion, which is why it was considered at last. Since there are frequent data gaps and also data errors in long time series, the stations had to be examined in this regard. A certain amount of missing data had to be accepted, as interpolation of five-minute values is not useful, especially because of the high variability of the heavy rain events of short duration. Also, the derivation of the precipitation amount in the five-minute interval using the data from other stations is out of the question in view of the spatial limitations of most HPE of short duration. Fortunately, the missing values were limited for the months of May to September. Another problem with the analysis could be data errors or unrealistic high values in the time series. These were removed with the help of a macro, which ensured that data gaps were created instead of five-minute values higher than 30 mm. Ultimately for some stations there were years that could not be included in the analyzes, as for less than 90 % of the days a suitable maximum value for the five minute, hourly or six hour precipitation could be calculated. These years were used as missing years in the trend analysis of intensity and frequency of HPEs. Also for the daily rainfall totals of the individual stations, gaps and data errors were found in datasets of the DWD, which were deliberately neglected because of their rarity.

4.2 Definition “heavy precipitation event”

HPEs are characterized by short duration and high intensity. But there are various types of calculation. These include threshold values, percentiles or return period of fixed values (BRASSEUR et al. 2017). For the definition of threshold values on an hourly, six-hourly and daily scale the values of warning level 2 of the DWD were adopted. This resulted in an hourly threshold value of 15 mm, a six-hourly threshold value of 20 mm, and a daily threshold value of 30 mm. Since the DWD does not set a threshold value for higher time scales, the definition of LAUER & BENDIX (2004) was used for the 5 minute threshold value (Table 4).

Threshold value = $\sqrt{5 * \mathrm{D} - \left(\frac{\mathrm{D}}{24}\right)^2}$ with D = minutes

Table 4: HPEs on different time scales, defined by LAUER AND BENDIX (2004) and DWD (2018c).

Temporal resolution	Threshold value	Origin
5 min	5 mm	Lauer and Bendix 2004
1 h	15 mm	Warning Level 2 - DWD
6 h	20 mm	Warning Level 2 - DWD
24 h	30 mm	Warning Level 2 - DWD

4.3 Linear Regression

In the analysis of the time series the linear regression was used. The linear regression is a statistical method that examines the extent to which an observed dependent variable can be explained by one or more independent variables. Here, the simple linear regression which considers only one independent (predictor) variable and one dependent (predictand) variable, for example x and y, was applied. The aim of the simple linear regression is to summarize the relationship between x and y with the help of a representative single line.

4.4 Data processing (import, formatting, analysis)

Data processing (import, formatting, analysis)

Step 1: Basic five-minute precipitation data (“stationname_Grunddaten.xlsx”)

For the extreme value and threshold analysis of high-resolution precipitation data, the five-minute data already mentioned in section 3.2 is the initial point of every analysis. To get the five-minute data into editable form first, the data has to be read into Excel and set into a suitable format. This results in 288 values per day (line wise) in five-minute increments (in columns). For the removal of data errors, all values larger than 30 mm are deleted from the data set, as this is an unrealistic value for the time scale of five minutes. This step is performed using a macro. A folder "bereinigte_Grunddaten_5min" with the raw data and the processed data can be found in the folder “Daten” of the attached memory stick.

Step 2: Basic daily precipitation data (“stationname_Tagesdaten.xlsx”):

For the comparison of precipitation events on different time scales (five-minute, hourly, and six-hourly) with daily totals, station data with daily precipitation resolution is also used. These are arranged similar to the five-minute data, but with only one column containing the daily total. Again, data errors (here larger equal 9999 mm) are deleted using a macro. These data can be found in the folder Daten \ Zwischendaten \ 1d.

Step 3: Basic daily Grosswetterlagen (“Grosswetterlagen.xlsx”)

The likewise documented daily weather conditions of both classifications are arranged differently. The days from the 1st of January to the 31st of December are arranged line by line, in columns the years from 1951 to 2015. These data can be found in the folder Daten\Grosswetterlagen for both classifications.

Including imported and processed data from Step 1 into templates

Step 4: “leer_5m_1h_1d.xlsx”

The processed five-minute data is then included in “leer_5m_1h_1d.xlsx” and calculations for daily maximum values in five-minute scale are made, as well as the number of exceedance of predefined threshold values (RR 5 min ≥ 5 mm, RR 1 h ≥ 15 mm, and RR 6 h ≥ 20 mm).

Furthermore mean and maximum values are computed for each time step (0:00 to 23:55) for the periods from 1961 to 1990 and from 1991 to 2015 for extended summer season (MJJAS) and on a monthly basis. In another step daily maximum values for hourly scale are calculated. In addition, five-minute data is converted into hourly data and daily data as well. With the help of pivot-tables and simple copy-and-paste these results later on are included in the template “stationname (Auswertung JD).xlsx”.

Step 5: “leer_5m_6h.xlsx”

Similar to the previous step imported and processed five-minute data are included in “leer_5m_6h.xlsx”. Equally, here daily maximum values on a six-hourly basis and number of exceedance of threshold values of 20 mm are computed and transferred into the template “stationname (Auswertung JD).xlsx” with the aid of pivot-tables.

Step 6: Final template “stationname (Auswertung JD)”

In the last step results of both previous processes are included in the final template named “stationname (Auswertung JD).xlsx”. Here the diurnal cycles of average and maximum precipitation for the periods 1961 to 1990 and 1991 to 2015 and the anomaly between these periods are shown. Furthermore calculations of annual cycles for maximum precipitation in different time scales (five minutes, one hour, six hours, and one day) are conducted. For the analysis of the exceedance of threshold values in relation to forcing GWLs, the daily GWLs (both the manually and the automatically version) are added in this template. To identify which GWLs that force HPEs, the number of exceedances of threshold values is assigned to the current GWL.

Collection and summary of the results

In order to summarize the results across all stations, a result file (“Collection_results.xlsx”) was created containing all the relevant results of the individual stations. Beneath the relevant results of each station the results averaged over the entire area of investigation are displayed. Furthermore within this file the statistical analysis of the results with the linear regression can be found. All results presented in this work (time series, annual and diurnal cycle, frequency of the GWLs of the GWLc and SVGc, and their frequency during HPEs) can be found in this file.

5 Results

The first part of this section deals with the time series and evolution of the 99th percentile of absolute maximum five minute, one hour, six hour and daily rainfall during the time span 1961 to 2015 from May to September. Additional, the frequency of events with exceedance of predefined threshold values are described. Thereafter (in section 5.2), the annual cycles of frequency of HPEs on five-minute and daily scale are compared. In section 5.3 the diurnal cycle of extended summer season's five-minute absolute maximum and average are brought into connection with HPEs caused by convection. In a last part (section 5.4) the seasonal frequency of the two classifications of the GWLs are introduced. With the help of the results of the previous section, heavy five-minute and daily precipitation events are related to the current GWLs in section 5.4.1. In section 5.4.2 highly heavy precipitation relevant GWLs are identified and the frequency of these GWLs from 1961 to 2015 is shown.

5.1 Trends in intensity and frequency of heavy precipitation events

5.1.1 Intensity of heavy precipitation events

Figure 3 displays the time series of the 99th percentile of maximum daily rainfall during the period 1961 to 2015 for each summer and its linear trend for different time scales (5 min, 1 h, 6 h, and 24 h) averaged over all stations. For all time scales positive linear trends were detected. For the 99th percentile of the five-minute maxima a trend of +0.041 mm per year was calculated averaged over all stations. Using the linear regression for the five-minute time scale, for almost all stations a significant positive trend in intensity was detected. Only the station Trier followed a non-significant positive trend. On hourly scale a trend of +0.038 averaged over all stations could be found. Although 18 of 19 stations show a positive trend the only positive significant trends were found for the stations Bad Hersfeld, Erfurt, and Magdeburg. For the station Trier a slightly negative but insignificant trend is visible. In addition, the trend is lower at six-hourly scale (+0.018), still positive in average but insignificant for all stations. For the daily scale a positive linear trend of +0.017

Station	5 min	1 h	6 h	24 h
Artern	**0.042**	0.037	0.021	0.048
Augsburg	**0.042**	0.049	0.063	0.037
Bad Hersfeld	**0.056**	**0.085**	0.014	0.019
Bad Kissingen	**0.040**	0.020	0.015	-0.016
Erfurt	**0.048**	**0.071**	0.049	**0.144**
Fichtelberg	**0.027**	0.061	0.062	0.118
Frankfurt	**0.048**	0.028	-0.047	-0.086
Göttingen	**0.048**	0.033	-0.025	0.033
Hannover	**0.025**	0.040	0.013	0.014
Harzgerode	**0.024**	0.043	0.031	0.029
Kleiner Feldberg	**0.064**	0.048	-0.041	-0.048
Lingen	**0.046**	0.021	0.030	-0.022
Magdeburg	**0.030**	**0.071**	0.081	**0.122**
Mannheim	**0.056**	0.012	-0.005	-0.049
Nürnberg	**0.040**	0.028	0.018	0.024
Oehringen	**0.048**	0.040	0.073	0.008
Saarbrücken	**0.040**	0.049	-0.015	-0.037
Trier	0.022	-0.009	-0.005	-0.008
Weissenburg	**0.044**	0.024	0.038	0.054
Averaged	0.041	0.038	0.018	0.017

Table 5: Linear trends of 99th percentile of daily maxima for the different time scales and stations [in mm per summer season]. Bold indicates significant trend tested with linear regression (α = 0.05).

averaged over all stations can be seen. The stations Erfurt and Magdeburg show a significant positive trend, while for the remaining stations no significant increase or decrease was identified. Comparing the individual summers on different time scales for daily and six-hourly maxima no particular pattern appears. For daily maximum highest values were reached in 1981 and 2007. The high values of the daily totals of the summer of 1981 and 2007 are in line with the rainy summers of those years. For the station Frankfurt am Main, for example, these summers (here classically defined as June, July, August) recorded above-average rainfall (378 mm and 300 mm) (HLNUG 2018d). The high values for the summers of 2002 and 2013 are more likely to be attributed to the precipitation masses that fell in Southern and Eastern Germany, which also led to the Elbe flood in those years (BPB 2013). These high values are still visible on the hourly time scale. An identification on the scale of the five-minute values is not possible because these events, which are mostly caused by convective processes, are locally very limited and therefore not coupled to such a high degree as large-scale precipitation of longer duration. In fact highest values for heavy precipitation on the five-minute scale were achieved since the year 2000 averaged over all stations. The summers with the most intensive rainfall events averaged over all stations were found for the years 2000, 2006, and 2007. The variability of the parameter of heavy precipitation becomes even clearer by comparing the percentiles of the single stations during the years of interest. Here, for the stations Trier (8.0 mm in summer 2003) and Bad Hersfeld (7.9 mm in summer 2007 and 8.0 mm in summer 2011) highest 99th percentiles were detected. The – on average – high values for the 99th percentile for the years 2000, 2006, and 2007 are due to less intense HPEs at special stations on five-minute scale, but therefore more heavy precipitation affected stations (not shown).

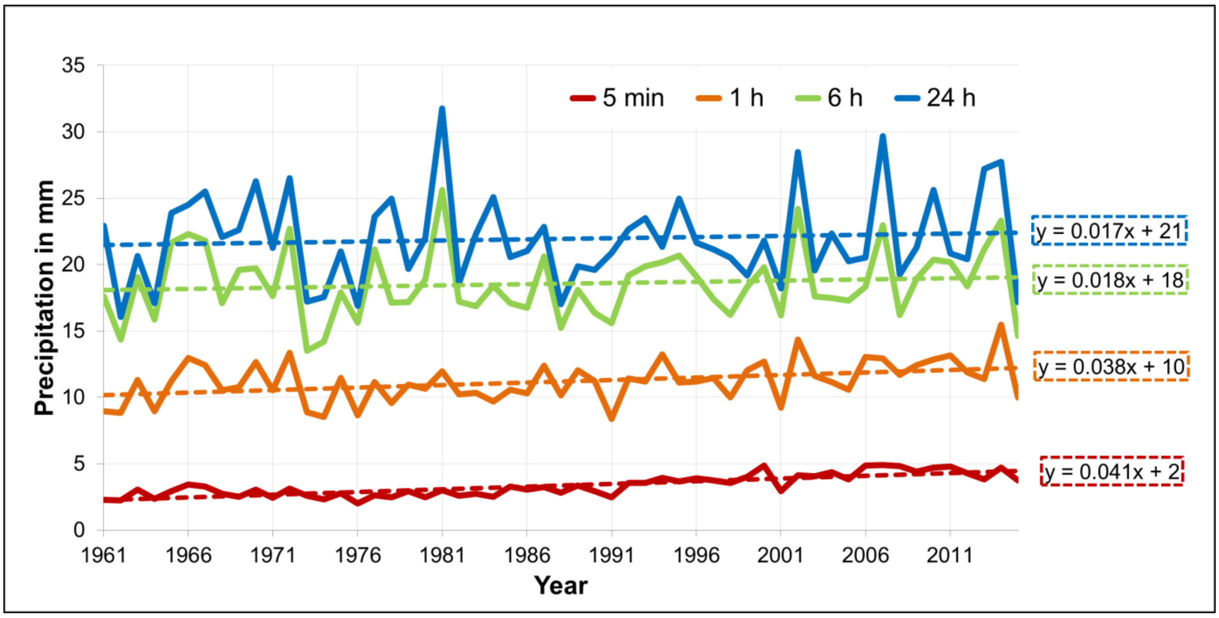


Figure 3: 99th percentile of daily maximum summer precipitation averaged over all stations during the period 1961 to 2015 [in mm]. Red (orange, green, blue) colours show 5 min (1 h, 6 h, 24 h) values.

All these calculations confirm the hypothesis of many studies (e.g. MÜLLER & PFISTER 2011 and FIENER et al. 2013) that the intensity of short duration events of high intensity and therefore erosion and flooding relevant events increased to a higher extent than events of longer duration and less intensity.

5.1.2 Frequency of heavy precipitation events

The temporal evolution of HPEs per year and per time scale is the subject of the following section. The number of days where the respective threshold value per time scale is exceeded is used. After the calculation a statement about the evolution of the excesses is possible. For the five-minute scale, as already mentioned in section 4.2, the threshold calculation by LAUER & BENDIX (2004) was used, resulting in a threshold value of rounded 5 mm. For the threshold values of the hourly, six-hourly and daily scales, the values of warning level 2 of the DWD were adopted. Table 6 and Figure 4 give an overview over the linear trend in the number of events exceeding the 5 mm threshold value for each station during the period 1961 to 2015 per year. Mannheim (+0.043), Kleiner Feldberg (+0.04) and Bad Hersfeld (+0.035) show the steepest positive trend, while the smoothest positive trends are calculated for Hannover (+0.009) and Trier (+0.007) which have insignificant tendencies. Overall, 15 of 19 stations have a positive significant tendency in number of HPEs on five-minute basis. Averaged over all used stations a increasing trend of +0.025 events per year was computed. In concrete terms, this means that HPEs occurred more frequently in the more recent years than in the early years of the investigated period 1961–2015. Figure 4 provides an overview over the spatial distribution of the trends. It shows that especially the stations in the centre of the area of investigation are affected by a steeper trend than the northern and western stations in terms of increasing frequency of five-minute high intensity events. However, it should not be unmentioned that an influence of the improved measurement technology at the beginning of the 1990s might have a considerable influence on the result of the trend analyzes of the five-minute period (see section 4.1).

Station	5 min	1 h	6 h	24 h
Artern	**0.021**	0.009	0.001	0.005
Augsburg	**0.030**	0.007	0.021	0.004
Bad Hersfeld	**0.035**	**0.013**	0.012	0.007
Bad Kissingen	**0.025**	0.008	0.001	-0.011
Erfurt	**0.031**	**0.013**	0.019	0.017
Fichtelberg	**0.023**	0.012	0.020	**0.020**
Frankfurt	**0.027**	0.008	-0.001	-0.011
Göttingen	**0.030**	0.008	-0.004	-0.004
Hannover	0.009	0.008	0.007	**0.011**
Harzgerode	0.014	-0.001	0.006	0.000
Kleiner Feldberg	**0.040**	0.011	-0.001	-0.006
Lingen	**0.023**	-0.002	-0.003	-0.002
Magdeburg	**0.025**	0.000	0.003	0.012
Mannheim	**0.043**	-0.002	-0.002	0.000
Nürnberg	**0.022**	0.006	0.011	0.002
Oehringen	**0.023**	**0.013**	0.018	0.000
Saarbrücken	**0.020**	**0.014**	0.000	**-0.018**
Trier	0.007	-0.012	-0.007	-0.009
Weissenburg	**0.030**	0.013	0.009	0.008
Averaged	0.025	0.006	0.005	0.001
Total	0.472	0.125	0.108	0.026

Table 6: Linear trends in number of HPE per summer season and station for a) five-minute, b) hourly, c) six-hourly, and d) daily scale during the period from 1961 to 2015. Green/red indicates positive/negative trend. Bold indicates significant trend tested with linear regression (α = 0.05).

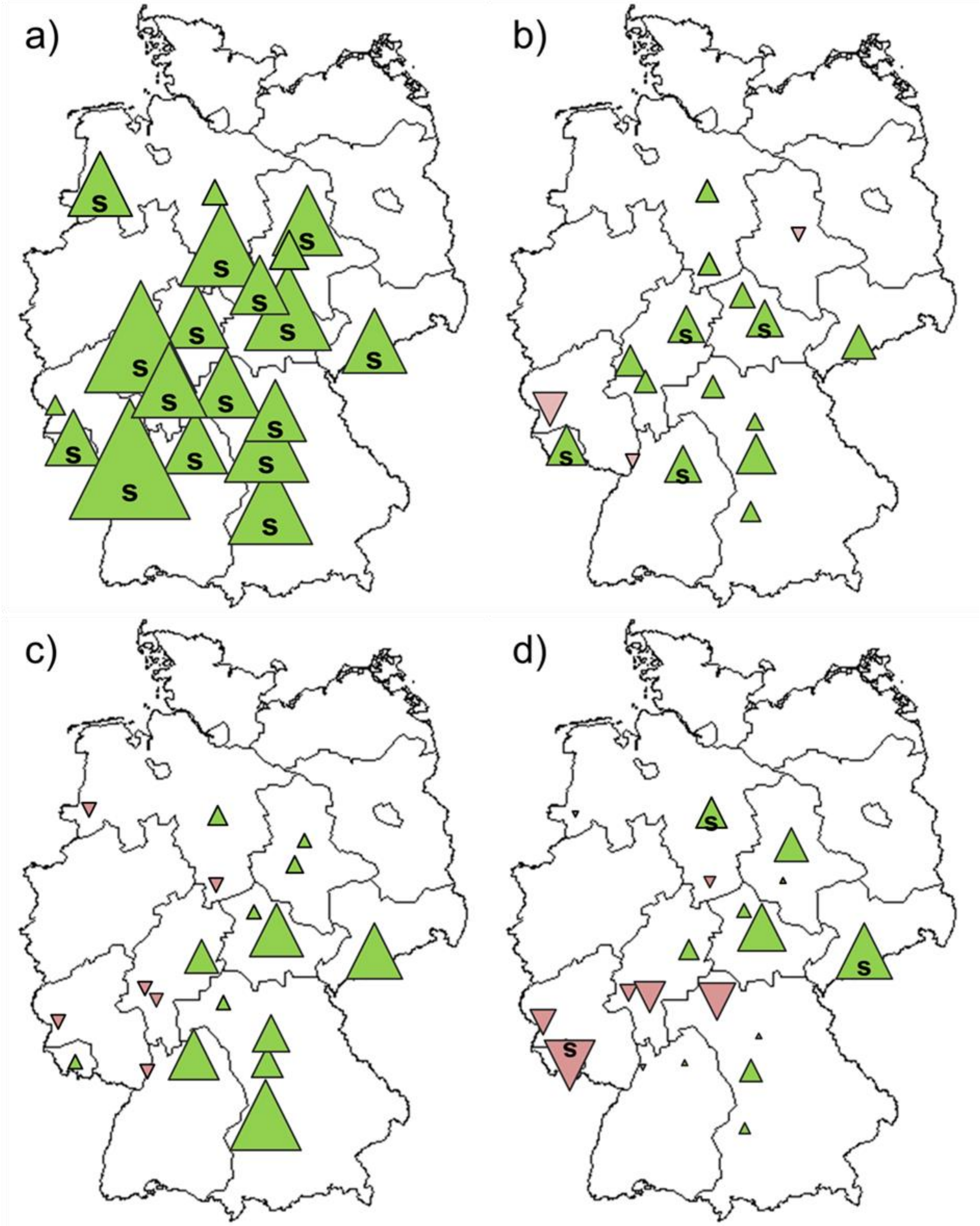


Figure 4: Map of linear trends in number of HPE per summer season and station for a) five-minute, b) hourly, c) six-hourly, and d) daily scale during the period 1961 to 2015. Green/red indicates positive linear trend. Stations marked with “s” indicate significant linear trend tested with linear regression (α = 0.05).

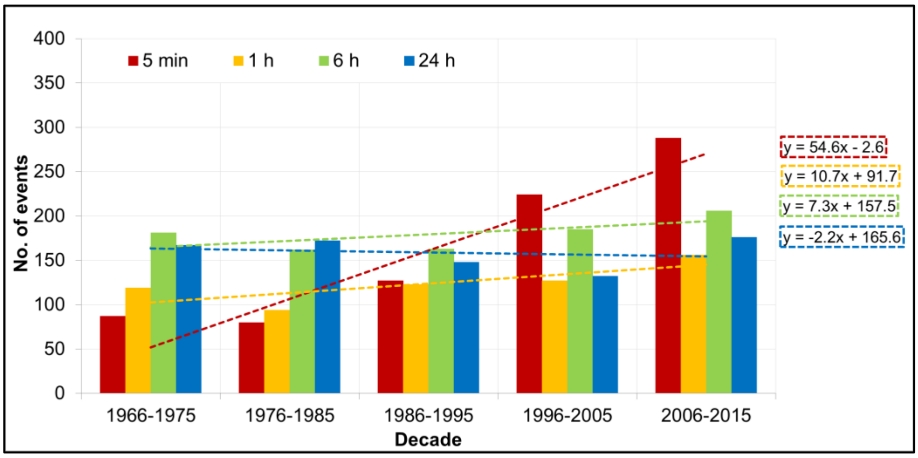


Figure 5: Number and linear trend of HPE on five-minute (hourly, six-hourly, daily) scale indicated by red (orange, green, blue) colour from the decade 1966–1975 to 2006–2015 observed over all stations.

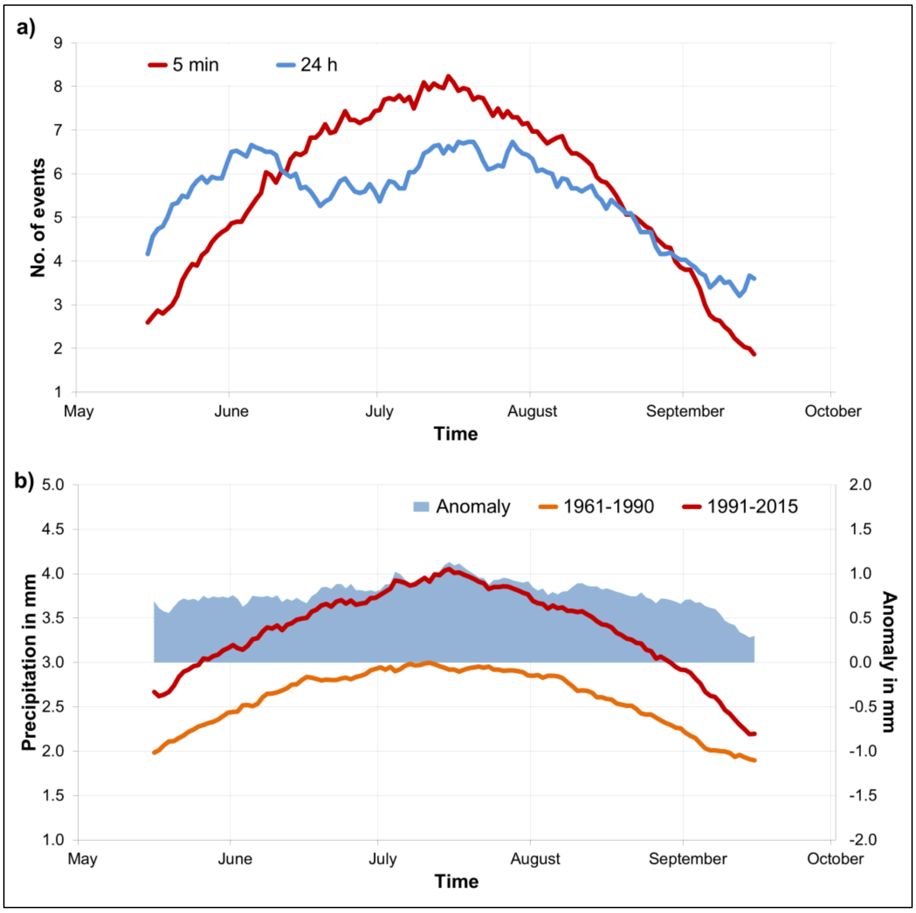
To illustrate the increasing frequency of HPEs, decadal frequencies of HPEs also were calculated (Figure 5). The respective number of events in the years 1966 to 1975, 1976 to 1985, 1986 to 1995, 1996 to 2005 and 2006 to 2015 were compared to ensure comparability of the values. It becomes clear that, especially for the high-intensity five-minute events, a sharp increase of +54.6 events per decade occurred. While 87 events exceeding the threshold value of more equal five millimeters in five minutes occurred in the years 1966-1975, the frequency decreased to 80 events in the next decade. But thereafter the number of events increased significantly, to a frequency of 288 in the past decade (2006-2015). For the further time scales such strong trends are not recognizable. The frequency of hourly events (+10.7 per decade) and six-hourly events (+7.3 per decade) increased, while daily events show a decrease (-2.2 per decade). A correlation of the increasing frequency of HPEs of short duration but high intensity to the occurrence of individual GWLs should be discussed in section 5.4.2, but still the relation to the change in instruments in the 1990s should also be taken into regard.

5.2 Seasonal cycle

As mentioned earlier, the annual cycle of mean precipitation in Germany is generally characterized by a double maximum in winter and summer combined with two minima in spring and autumn. The analysis of the annual cycle of HPEs, however, was limited on the months May to September due incomplete data. Anyhow, in these months the more extreme events are expected on short time scales. The maximum in winter is due to frontal passages, which usually do not lead to short-term high-intensity precipitation in the five-minute frame, but rather persist over a longer period. The situation is different with the short-term HPEs in summer, which are assigned to convective conditions and are therefore of higher relevance for this work. Figure 6a shows the frequency of HPEs on five-minute and daily scale per day in a 30-day-smooting. On the five-minute scale most HPEs were detected for mid-July. This could mainly be attributed to convection driven by high solar radiation and higher air temperatures. The principle of convection has been explained in the introduction in section 2.4.. The frequency of HPEs on daily scale shows a double-wave from May to

September, with maxima in the beginning of June and mid-July. This course could be attributed to both convective processes and atmospheric circulation. Additionally, figure 6b compares the seasonal cycles of daily maxima of five-minute precipitation averaged over the entire area of investigation during May to September for the periods 1961–1990 and 1991–2015. It is obvious that the averaged maximum values of the stations in the later period exceed those of the first period over the entire annual cycle. As mentioned earlier, this clear transgression is likely to have climatic causes, but most likely to be caused by measuring technology change as well, which is particularly relevant to the conversion of the measuring technology in the 1990s. An increase in average between 0.5 and 1 mm should be too high within such a short period of 55 years.

Figure 6: Annual Cycle of heavy precipitation. a) Absolute number of high-intensity precipitation events for 5 min (RR ≥ 5 mm) and daily scale (RR ≥ 30 mm) within 1961 – 2015 at all stations (30-day-smoothing). b) Seasonal cycle of high-intensity precipitation for 5 min maxima of the periods 1961–1990 and 1991–2015 and anomalies averaged over all stations.



5.3 Diurnal cycle

The analysis of the five-minute data in this study shows the approach of a double wave of mean precipitation averaged over all stations in the diurnal cycle (Figure 7a). In the diurnal cycle of the individual stations, however, the secondary maximum in the early morning is sometimes less pronounced or partially absent. Since, the present work focuses on the strong main peak towards afternoon, which is not only visible averaged over all stations but also in the analysis of the individual stations, the secondary maximum will be given no further consideration in the following. The main maximum which occurs around 16:30 UTC averaged over all stations could be attributed to convective precipitation events. These are triggered by the increased solar radiation and concomitant high heating at the bottom and the lower air layers. This warming results in a labialization of the air layers caused by the rise of warm air. Figure 7b shows the diurnal cycle of maximum precipitation during summer months (May to September) for the periods 1961–1990 and 1991–2015. Here the double wave for both periods is obvious. The main maximum is detected in the afternoon for both periods and minimum at 09:00 to 10:00 UTC. By comparing diurnal cycles of both periods a higher maximum precipitation over the whole period 1991–2015 becomes apparent (blue shaded). As already noted in the last section, the higher values for the later period are likely to be due to an intensification of heavy precipitation as well as measuring technology changes in the 1990s.

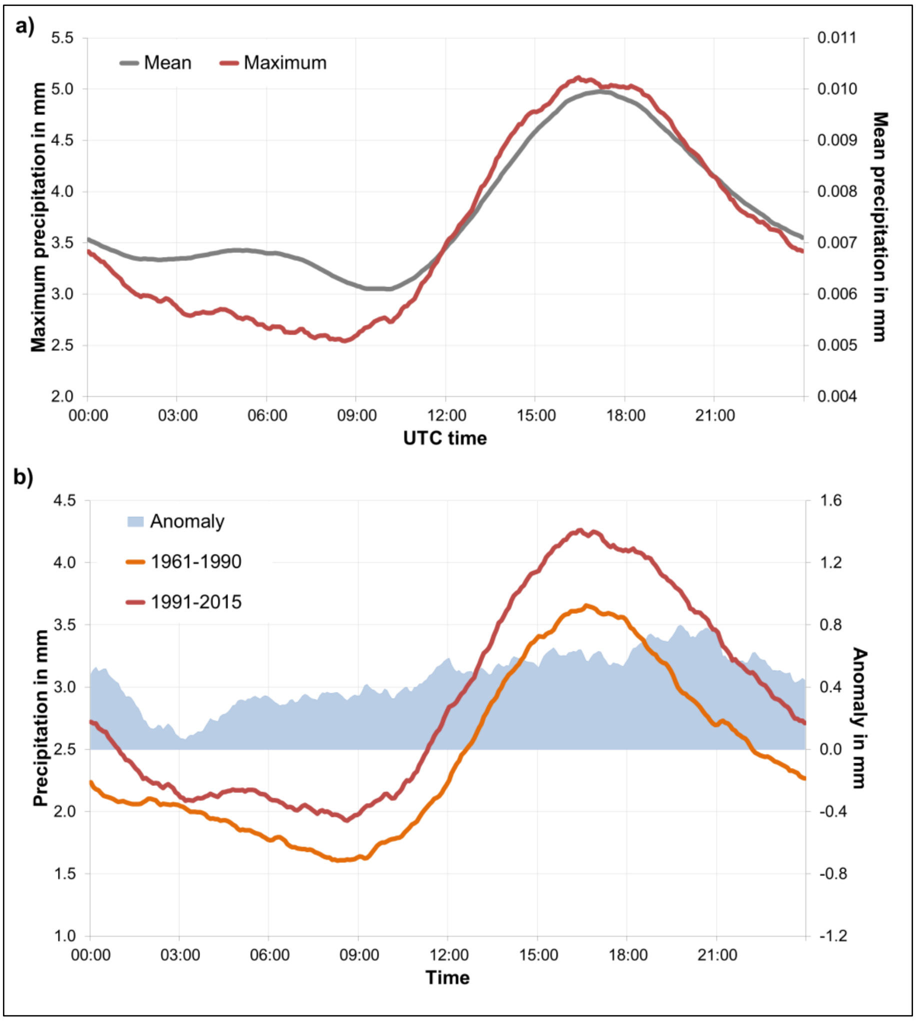
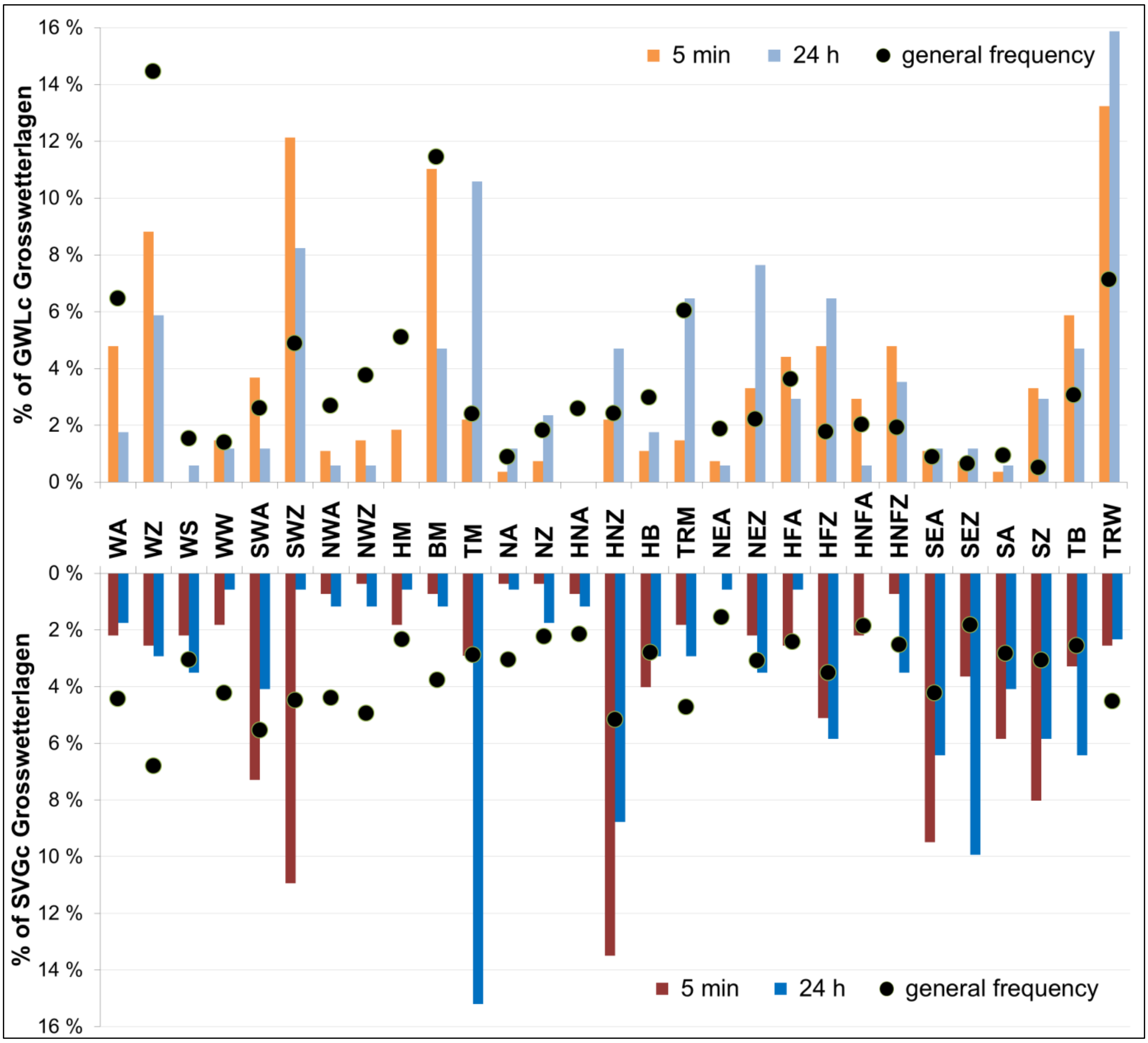


Figure 7: Diurnal cycle of precipitation. a) Diurnal cycle of mean and maximum five-minute precipitation during the period 1961–2015 averaged over all stations. The grey / red graph represents the mean / maximum five-minute precipitation sum. b) Diurnal cycle of maximum five-minute precipitation during the period from1961 to 1990 and 1991 to2015 and anomalies averaged over all stations.

5.4 Atmospheric circulation: Daily Grosswetterlagen (1961–2015)

Since weather is generally strongly influenced by the atmospheric circulation, a consideration of this aspect is also of great importance in the investigation of HPEs. This section reveals an overview over the atmospheric circulation during the summer seasons 1961 to 2015 with help of the GWLs, which were introduced in section 3.3. Furthermore the occurrences of HPEs on five-minute and daily scale are investigated on current GWLs in section 5.4.1.

Figure 8: HPEs on five-minute and daily scale and relative frequency of each Grosswetterlage during these events. The top/bottom half of the figure displays results for GWLc/ SVGc. The black points indicate general relative frequency of the different Grosswetterlagen during summer months.



The comparison of percentage occurrence of GWLs per day classified with the GWLc and the SVGc during summer season 1961 to 2015 is given in Figure 8 (black points). When considering the relative frequency of occurrence of individual GWLs, it is striking that these differ depending on whether the subjective (GWLc) or the objective version (SVGc) is taken into focus. While some particular GWLs dominate in the subjective classic version in the summer months of May to September in the period from 1961 to 2015, the objective automatic version shows a more evenly distributed relative occurrence of the GWLs. To clarify this statement, it is worth taking a closer look at Figure 8. Considering only the upper part of the figure, which shows the relative abundance of the GWLc, the GWLs WZ (14.3 %) and BM (11.3 %) occur to highest frequency over the whole period. The lower half of the figure characterizes the relative frequency of the GWLs of the SVGc. Such a dominance of a few GWLs as within the GWLc is not observable. Although certain GWLs such as WZ (6.7 %), SWA (5.5 %), and HNZ (5.1 %) appeared more frequently than others over the entire period, enormous differences as in the classic version do not occur here. Rather, the distribution of the GWLs here is more evenly distributed. In summary it can be stated that both Grosswetterlagen classifications differ enormously from each other and that they must be considered separately from each other. The next section focusses on the connection between the occurrence of different GWL and high-intensity rainfall events on five-minute and daily scale. An analysis of the hourly and six-hourly events was deliberately omitted under the premise of clarity.

5.4.1 Heavy precipitation events and related Grosswetterlagen

Figure 8 also establishes a connection between HPEs occurring in the five-minute and daily scale and the associated relative abundance of the individual GWLs. This allows a comparison of the extent to which certain GWL is predestined for five-minute or daily HPEs. All information is made in percentage to ensure a simpler overview. The evaluations refer to days where at least at two of the 19 stations rainfall events were observed. These were 274 days with heavy rainfall in the five-minute scale (≥ 5 mm), as well as 171 days with daily totals ≥ 30 mm. The upper half of the figure, as introduced in the previous section, uses the GWLc as basis for atmospheric circulation.

It is noticeable that some GWLs prevailed in the context of five-minute as well as daily HPEs. This is especially true for the GWL TRW (13.2 % during five-minute events [in orange] and 15.9 % for daily events [in light blue]). So during this GWL both high-intensity rainfall in the short term and high daily totals can be expected. This also applies to the GWLs WZ (8.8 % and 5.9 %), SWZ (12.1 % and 8.2 %), and BM (11 % and 4.7 %), which were observed to a higher extent during five-minute HPEs. Other GWLs that are more likely to experience high-intensity short-term precipitation include WA, SWA, and TB. This is not the case with the GWL TM, where higher daily totals were detected (2.2 % and 10.6 %). Also the GWLs NEZ (3.3 % and 7.6 %), TRM (1.5 % and 6.5 %), and HFZ (4.8 % and 6.5 %) provided rather high daily totals than heavy short-term precipitation.

The lower half of the figure shows the same evaluation for the SVGc. Here, the short-term precipitation-promoting characters of the GWL HNZ and the GWLs with southern or eastern inflow SWZ, SEA, SZ, SWA, SA, and HFZ become clear. Daily high precipitation totals were often observed during the GWLs TM, SEZ, HNZ, TB, SEA, HFZ, SZ, and SWA.

Comparing the relative frequency of the GWLs during both time scales, the high value for the GWL TM (2.9 % on five-minute scale and 15.2 % on daily scale) becomes obvious. This is similar to the HPEs and their relationship to the GWLs of the GWLc. Therefore this GWL is predestined for high daily totals. Other GWLs that are more connected to high daily totals are SEZ (3.6 % and 9.9 %) and TB (3.3 % and 6.4 %). In contrast to that, the GWLs SWZ (10.9 % and 0.6 %), SWA (7.3 % and 4.1 %), SEA (9.5 % and 6.4 %), and SZ (8 % and 5.8 %), which are often associated with heat waves in Germany tend to cause heavy precipitation in the short-term. However, the general frequency of the individual GWLs should not be disregarded, since a relatively high frequency of a particular GWL could lead to high frequency of heavy rain events within this GWL days. In order to gain an impression of which GWLs are particularly highly relevant for HPEs on the five-minute scale, section 5.4.2 shows the percentage of the GWL days where at least two locations in the study area detected heavy rainfall.

To emphasize that the two classifications are highly different and must therefore be considered separately is shown in Figure 9. Therefore the results for the both classifications of Figure 8 were compared and anomalies were identified. Especially for the differences in heavy rain-promoting GWLs with southern and eastern currents and the special case of the northern HNZ (as to be shown in the next chapter) occurred. These are much more pronounced within the SVGc than in the GWLc. Within the GWLc the GWLs WZ, BM and TRW are connected to a higher extent to HPEs than within the SVGc.

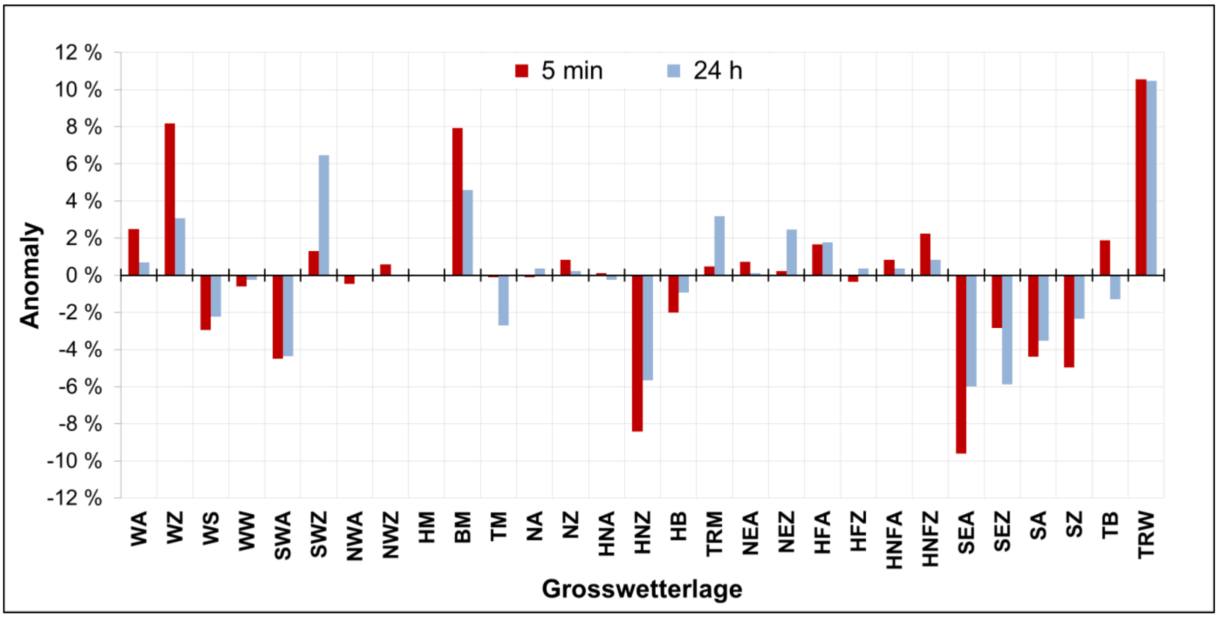


Figure 9: Anomalies between the GWLc and SVGc related to the frequency of certain GWL during HPEs in five-minute (red) and daily (blue) scale. Positive (negative) values indicate a higher frequency during HPE within the GWLc (SVGc).

5.4.2 Identification of highly heavy precipitation relevant Grosswetterlagen

HPEs of short time scales are primarily dependent on high lability of the air layers caused by differences in temperature in the lower layers (warm) and upper layers of air (cooler). This process is associated with free uplift. In detail the air is heated near the ground, while the upper layers of air are colder. As warm air rises, the lability of the air layers required for heavy rainfall is reached. If these warm air masses have enough water vapor content, an elevation and corresponding cooling of the air masses leads to the development of a convective event. However, the so-called slope rain, which arises on the windward sides of the mountains, is of importance, too. This process referred to as forced uplift, cause the wind to push up the air masses uphill. This leads to a cooling of the air and condensation and in turn precipitation. If the transported air is particularly humid, these processes may lead to heavy rainfall, which can also be significant in the five-minute interval (HOY & HÜBENER 2018).

Since the presence of warm air in the lower air layers is a factor for the origin of HPEs in the short-term, it is assumed that GWLs with southerly and easterly inflow to Germany have a higher proportion of HPEs in the short-term. This is more difficult for heavy rain events with high daily totals. These are usually caused by precipitation of longer time scales and lower intensity. These are triggered by stratiform and convective processes. The GWL TM is suspected to cause relatively high daily totals with the formation of stratiform clouds, but also the GWLs with southern or eastern inflow trigger high daily totals due to their convective character. However, on five minute scale warm and humid air masses of southern or eastern origin would be expected to promote convective processes and therefore HPEs on this time scale.

Table 7: Classification of the summer characteristics of the individual GWL with the properties cooler (blue), warmer (red), wetter (green), and drier (yellow) according to HOY et al (2013).

GWL	WA	WZ	WS	WW	SWA	SWZ	NWA	NWZ	HM	BM	TM	NA	NZ	HNA	HNZ	HB	TRM	NEA	NEZ	HFA	HFZ	HNFA	HNFZ	SEA	SEZ	SA	SZ	TB	TRW
colder/warmer		x	x				x	x			x	x	x		x	x	x		x										
	x			x	x	x			x	x				x				x		x	x	x	x	x	x	x	x	x	x
wetter/drier		x	x	x		x		x			x		x		x		x		x				x					x	x
	x				x		x		x	x		x		x		x		x		x	x	x		x	x	x	x		
inflow direction	W				SW		NW		–		–	N						NE		E				SE		S			

For the remaining steps of this work such heavy precipitation-promoting GWLs had to be identified not only by adopting from the references and theoretical assumptions but by evaluations with the help of the given data. Since the station data used in this work comes from spatially scattered stations with different location characteristics, convective events are not completely fixed to specific GWLs, because the various GWLs have quite differentiated effects on the individual stations. This fact complicates the generalization to a larger study area with several station aspects. Nevertheless, a grouping of "highly heavy precipitation relevant" GWLs at this point makes sense, since individual GWLs are quite more predestined for the formation of convective precipitation in the study area. In order to ensure a high degree of representativeness of the GWLs with regard to their heavy precipitation-promoting character for the entire study area, the individual GWLs were examined to which percentage of days of a particular GWL a heavy rain event in the five-minute interval was observed at at least two stations of the study area. Those GWLs, which were observed in combination to HPEs at two or more stations in more than 5 % of their occurrence, were rated as convection promoters. Table 8 gives an overview of the heavy precipitation-relevance of the individual GWLs. It is shown that for the GWLc the GWLs SWZ, HFZ, HNFZ, SZ, TB, and TRW were evaluated as “highly convection relevant” for the area of investigation. All these GWLs include southern or eastern inflow directions. The analysis for the SVGc gives a similar, but not the same impression. Here the GWLs SWZ, SEZ, SEA, SA, and SZ are classified as “highly heavy precipitation relevant”. All of them include southern components. But also the GWL HNZ plays an important role in the frequency of HPEs of short duration. The relevance of most GWLs in heavy precipitation is due to the southern or eastern component. At first glance, an exception is the HNZ, which is classified as northern type. The question arises, why this GWL often leads to heavy rain events on short-time scales. The answer lies in the effect of cold air pools over Western Europe or western Central Europe. This high altitude low pressure area is filled with cold air, which flows through a trough directed from Scandinavia to the southwest, and thus brings cool air masses in the height to central Europe. The resulting increased risk of labialization is the driver of heavy precipitation, if the criterion of existing moisture is met.

Table 8: Conditional frequency of days with high-intensity 5 min-events and daily events at 2 or more (of 19) stations per Grosswetterlage within GWLc and SVGc. Grosswetterlagen with frequencies >5 % (GWLc in green, SVGc in purple) are defined as “highly heavy precipitation-relevant”.

Grosswetterlage	5min		24h		Inflow
	GWLc	SVGc	GWLc	SVGc	
WA	2%	2%	1%	1%	W
WZ	2%	1%	1%	1%	
WS	0%	2%	1%	2%	
WW	3%	1%	2%	0%	
SWA	5%	4%	1%	2%	SW
SWZ	**8%**	**8%**	3%	0%	
NWA	1%	1%	0%	1%	NW
NWZ	1%	0%	0%	0%	
HM	1%	3%	0%	1%	–
BM	3%	1%	1%	1%	
TM	3%	3%	**9%**	**11%**	
NA	1%	0%	3%	0%	N
NZ	1%	1%	3%	2%	
HNA	0%	1%	0%	1%	
HNZ	3%	**9%**	4%	3%	
HB	1%	5%	1%	2%	
TRM	1%	1%	2%	1%	
NEA	1%	0%	1%	1%	NE
NEZ	5%	2%	**7%**	2%	
HFA	4%	3%	2%	0%	E
HFZ	**9%**	5%	**7%**	3%	
HNFA	5%	4%	1%	0%	
HNFZ	**8%**	1%	4%	3%	
SEA	4%	**7%**	3%	3%	SE
SEZ	4%	**7%**	4%	**11%**	
SA	1%	**7%**	1%	3%	S
SZ	**21%**	**9%**	**12%**	4%	
TB	**6%**	4%	3%	**5%**	
TRW	**6%**	2%	5%	1%	

5.4.3 Frequency of heavy precipitation relevant Grosswetterlagen

The results from the previous section, where strongly heavy precipitation-promoting GWLs were identified, allowed the calculation of a temporal course of the frequency of these GWLs during the period of investigation. For the manual Grosswetterlagen classification (GWLc) a significant increasing frequency of strongly heavy precipitation-promoting GWLs of +0.2028 per year is shown (Figure 10). For the automated classification (SVGc) a smoother and non-significant increasing frequency of +0.0597 per year was detected. Thus, such a large increase in the incidence of HPEs cannot be explained by an increase in heavy precipitation-promoting GWLs alone. Rather, other factors play an important role in the development of HPEs.

Figure 10: Frequency and trend of heavy precipitation relevant GWL per summer season during the period 1961 to 2015. Green (purple) contains heavy precipitation relevant GWL of the GWLc (SVGc).

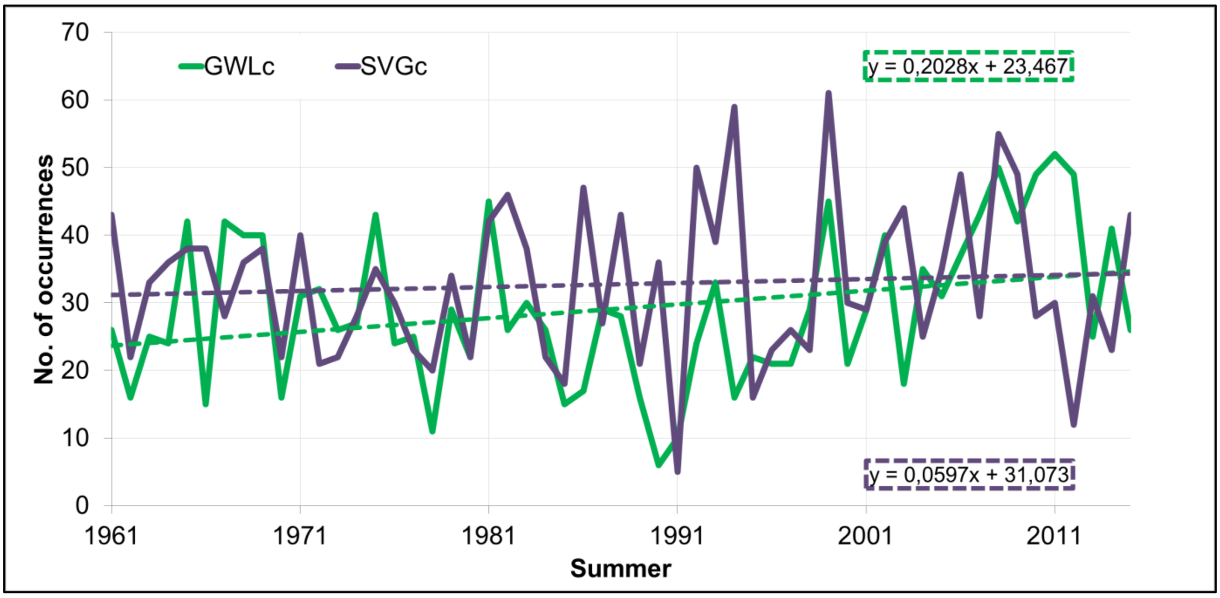


Table 9 shows the frequency of HPEs observed at the individual stations as a function of the frequency of the individual GWLs. However, here the absolute frequencies of the five-minute heavy rain events, which at the various stations are partly filled with data gaps, have been related to the gapless recording of the GWLs. Nevertheless, a tendency of events during individual GWLs is visible. Considering the GWLc, these are mainly the GWLs with the southern component (SWZ, SEA, SEZ, SZ, TB and TRW) and with the eastern component (HFZ, HNFZ), which bear an increased risk of heavy rainfall for the majority of the individual stations. Particularly the GWL SZ stands out with many stations and comparatively high percentage danger. For the SVGc an increased heavy rain risk for the GWLs SWZ, SEA, SEZ, SZ, and TB has also been identified, while the GWL TRW id attributed with lower heavy rain potential and HNZ is gaining importance for significantly more stations.

Table 9: Risk of heavy precipitation events on five-minute time scaleper station and GWL on the basis of a) GWLc and b) SVGc.

a) **GWLc**	**WA**	**WZ**	**WS**	**WW**	**SWA**	**SWZ**	**NWA**	**NWZ**	**HM**	**BM**	**TM**	**NA**	**NZ**	**HNA**	**HNZ**	**HB**	**TRM**	**NEA**	**NEZ**	**HFA**	**HFZ**	**HNFA**	**HNFZ**	**SEA**	**SEZ**	**SA**	**SZ**	**TB**	**TRW**
Artern	1%	0%	1%	2%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	5%	2%	2%
Augsburg	0%	0%	0%	1%	0%	1%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	4%	0%	2%	1%	1%
Bad Hersfeld	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	3%	1%	0%	4%	0%	0%	5%	2%	2%
Bad Kissingen	0%	1%	1%	0%	1%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	2%	2%	0%	3%	0%	0%	0%	0%	0%
Erfurt	0%	0%	0%	1%	1%	2%	0%	0%	0%	1%	2%	0%	1%	0%	0%	0%	0%	0%	1%	0%	1%	1%	1%	1%	2%	0%	2%	1%	2%
Fichtelberg	1%	0%	0%	1%	0%	3%	0%	0%	0%	1%	1%	0%	0%	1%	0%	0%	0%	0%	1%	0%	1%	1%	0%	1%	2%	1%	2%	1%	1%
Frankfurt	1%	0%	0%	1%	1%	1%	0%	1%	0%	0%	2%	0%	0%	0%	2%	0%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	2%	0%	1%
Göttingen	0%	1%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	1%	2%	1%	0%	0%	1%	1%	0%	0%	0%	0%	1%
Hannover	0%	0%	0%	2%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	1%	0%	0%	0%	0%	1%
Harzgerode	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%	1%	0%	0%	3%	2%	2%	0%
Kleiner Feldberg	0%	0%	0%	1%	1%	2%	1%	0%	1%	1%	0%	0%	1%	0%	0%	0%	0%	1%	0%	1%	1%	0%	1%	1%	0%	3%	7%	1%	1%
Lingen	0%	1%	0%	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	3%	0%	0%	1%	5%	3%	1%
Magdeburg	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	1%	1%	1%	0%	2%	0%	0%	0%	5%	2%	1%
Mannheim	1%	1%	0%	1%	0%	1%	0%	1%	0%	0%	2%	1%	0%	0%	0%	0%	0%	1%	0%	0%	3%	2%	2%	1%	0%	0%	5%	1%	1%
Nürnberg	1%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	1%	0%	2%	0%	1%	3%	2%	0%	0%	2%	1%
Oehringen	0%	1%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	2%	0%	0%	1%	1%
Saarbrücken	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	1%	0%	1%	0%	0%	1%	0%	1%	1%	1%	1%	0%	0%	0%	2%	0%	0%	0%	1%
Trier	0%	0%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	1%	0%	0%	1%	2%	0%	0%	0%	0%	1%	0%
Weissenburg	0%	1%	0%	2%	0%	2%	0%	0%	0%	1%	2%	1%	0%	0%	1%	0%	0%	0%	1%	1%	1%	2%	1%	0%	0%	0%	0%	1%	1%

b) **SVGc**	**WA**	**WZ**	**WS**	**WW**	**SWA**	**SWZ**	**NWA**	**NWZ**	**HM**	**BM**	**TM**	**NA**	**NZ**	**HNA**	**HNZ**	**HB**	**TRM**	**NEA**	**NEZ**	**HFA**	**HFZ**	**HNFA**	**HNFZ**	**SEA**	**SEZ**	**SA**	**SZ**	**TB**	**TRW**
Artern	0%	0%	1%	0%	1%	2%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	1%	1%	1%	2%	1%	1%
Augsburg	0%	0%	0%	0%	1%	1%	1%	0%	1%	0%	0%	0%	0%	0%	3%	1%	0%	0%	0%	0%	1%	1%	0%	1%	1%	0%	2%	0%	1%
Bad Hersfeld	0%	1%	0%	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	2%	2%	0%	2%	1%	0%
Bad Kissingen	1%	0%	0%	0%	1%	1%	0%	0%	1%	0%	0%	0%	0%	1%	2%	0%	0%	0%	1%	0%	0%	1%	0%	1%	0%	0%	1%	0%	1%
Erfurt	0%	0%	0%	1%	1%	1%	0%	0%	1%	0%	1%	0%	0%	0%	2%	1%	0%	0%	0%	0%	1%	1%	0%	1%	1%	2%	2%	0%	0%
Fichtelberg	0%	1%	0%	1%	1%	1%	0%	0%	1%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	2%	0%	0%	2%	1%	1%	2%	1%	0%
Frankfurt	0%	0%	1%	0%	1%	2%	0%	0%	1%	0%	2%	0%	1%	0%	1%	1%	1%	0%	0%	0%	0%	1%	1%	1%	0%	1%	0%	1%	0%
Göttingen	1%	0%	2%	0%	0%	1%	0%	0%	1%	1%	0%	0%	0%	0%	1%	1%	0%	0%	1%	0%	0%	0%	0%	2%	1%	0%	0%	0%	1%
Hannover	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	2%	0%	0%
Harzgerode	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	1%	1%	1%	1%	1%	1%
Kleiner Feldberg	1%	1%	0%	0%	2%	1%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	1%	0%	0%	0%	1%	0%	1%	0%	1%	2%	2%	1%
Lingen	0%	0%	1%	1%	0%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	1%	3%	2%	1%	0%
Magdeburg	0%	0%	1%	0%	1%	1%	0%	0%	0%	0%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	0%	1%	3%	1%	1%	0%	1%
Mannheim	1%	1%	1%	0%	1%	2%	0%	0%	2%	0%	0%	0%	0%	1%	1%	1%	1%	0%	0%	1%	1%	1%	0%	1%	3%	0%	2%	1%	0%
Nürnberg	0%	0%	1%	1%	0%	2%	0%	0%	2%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	1%	1%	0%	1%	1%	1%	1%	1%	0%
Oehringen	0%	0%	0%	1%	1%	3%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	1%	0%	1%	1%	1%	0%	0%	1%
Saarbrücken	0%	0%	1%	1%	0%	1%	1%	0%	1%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	1%	1%	0%	1%	1%	0%	0%	0%	0%
Trier	0%	0%	1%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	1%	2%	0%	0%	0%	0%	0%	1%	0%	0%	1%	1%	1%	1%	0%	0%
Weissenburg	0%	1%	1%	1%	1%	2%	0%	0%	1%	1%	0%	0%	0%	1%	2%	2%	0%	0%	0%	0%	0%	1%	1%	2%	1%	1%	1%	1%	1%

6 Discussion

The five-minute data used to calculate the frequency and intensity of HPEs is not completely homogeneous due to possible measurement errors. This means, as explained in section 3, unnaturally high values of larger equal 30 mm and error values (99999 and 99998) have been removed from the five-minute data records. As a result, in addition to the already existing data gaps, more data gaps have been added. To what extent these erroneous values came about through measurement and device errors could not be clarified. In order to get an idea of the extent to which the existing data gaps could affect the results, the five-minute values were totalized to daily totals and compared to the daily totals from the Hellmann measurements. It was found that for most stations systematically until the 1990s lower daily totals for the totalized five-minute values were calculated in comparison to the daily totals from the Hellmann data. However, reverse findings were also made for individual stations. In order to unambiguously demonstrate an influence of the measurement technology change in the early 1990s, parallel measurements of both high-resolution techniques could be an adequate way to compare both techniques. In the context of this bachelor thesis, however, a study of this has not been done, so that - as in the study of high resolution rainfall data - there are usual residual doubts. Nevertheless, it can be assumed that the trends in intensity and frequency found here are more instrumental than climatological driven in nature. In general, the analysis of convection-triggered and thus small-scale precipitation events based on station data is a difficult and erroneous undertaking, which further complicates generalization to a large study area. The observation of precipitation with radar may be a solution to achieve more reliable results in much higher spatial resolution. However, the hourly data generated from radar and station data within the framework of the RADOLAN project is only available since the year 2001. This limits the climatological validity of the derived products. In particular, the analysis of extremely intense and rare events that have great potential for damage is affected. Nevertheless the RADOLAN products provided insights into the distribution and frequency of HPEs that cannot be provided by analysis of station data (WINTERRATH et al. 2017).

It must also be taken into account that the analyzed data started in the 1960s. Previous studies have shown that the 1950s were rainier and that incorporating data from the 1950s may lead to less strong trends. However, the extent to which this would affect the high resolved precipitation data and the trends computed in this work could not be clarified due to missing or to incomplete data.

Comparing the results of this work with the results of FIENER et al. (2013), parallels become apparent. An increasing frequency of heavy rain events on short time scales was found in both works. A significant upward trend in the frequency of HPEs in the five-minute scale was detected for 14 out of 19 stations in the study, while an increasing but not significant trend was calculated for the remaining stations (section 5.1.2). Furthermore, just like shown in the present study, FIENER et al. (2013) calculated an increase in intensity for the strongest events, too (5.1.1). Also MÜLLER & PFISTER (2011) found increasing frequency of heavy rain events and diagnosed a multiplication of erosion relevant HPEs within only a few decades. Furthermore, they provided evidence of increasing mean annual and seasonal temperatures as well as altered atmospheric circulation, with increasing risk potential for HPEs. However, MÜLLER & PFISTER (2011) pointed out that the precipitation data used prior to the 1990s was only available in paper form and could be faulty due to digitization, instrumental errors (a blockade or incorrect settings) or the measuring technique digitization. But they referred to extremely high-resolution one-minute data and pointed out the increasing security of measurements with lower resolution already in the five-minute range.

HPEs with high intensity and on short time scale are more likely to occur during high-insolation days and hours. The analysis of maximum values and frequency of HPEs in the five-minute time scale brought expected results for the annual and diurnal cycle. These results could be confirmed by the analysis of the annual and diurnal cycle of heavy precipitation in sections 5.2 and 5.3. In addition BERG & HAERTER (2011) used temporally high-resolution precipitation data (in five-minute scale) to find out that average precipitation follows a certain annual and diurnal cycle. With the help of cloud cover data (in three hourly resolutions) they differentiated to what extent convective or stratiform cloud types prevailed in the summer months of the used inland stations. They have shown a high mid-summer maximum and an afternoon maximum of the frequency of convective cloud types. They also found a correlation between the observation of convective cloud types and the frequency of precipitation events in the diurnal cycle. The evaluation in the present work confirms the results of an annual and diurnal cycle of precipitation. These became especially visible in the evaluation of the seasonal cycle of the five-minute maxima averaged over all stations (Figure 6b) and the frequency of HPEs during the summer months (Figure 6a). However, no comprehensive data on cloud cover was available for the present study, a differentiation between stratiform and convective precipitation could only be performed with the help of the GWLs discussed in section 5.4. Since these are classified over a period of one day and thus small-scale convective types of clouds and also convective precipitation could not be identified with certainty, the analysis with the GWLs must be sufficient here. It should also be mentioned that - as pointed out by BERG & HAERTER (2011) - the temperature has a tremendous influence on the formation of convective precipitation. Therefore GWLs that bring warm and sufficient moisture-containing air from the southern and eastern direction are highly attributed to HPEs.

The diurnal cycle of precipitation has so far been the subject of scientific research. STEINHAUSER (1965) investigated the diurnal cycle of precipitation in Vienna (Austria) from 1901 to 1963 on seasonal anomalies. For summer-season he found that the daily course of precipitation followed a double wave. This corresponds to the results of this study that is focused on diurnal cycle of maximum and mean precipitation averaged over all stations. The interpretation of the secondary maximum around sunrise is relatively difficult. STEINHAUSER (1965) attributed it to processes in the free atmosphere and at the cloud tops. He also concluded that the latent warming on the ground and the lower layers of the air provide for a labialization of the air layers and trigger convective precipitation, which are responsible for the maximum in the afternoon.

In order to establish a correlation between certain GWLs and HPEs percentage information on the occurrence of all GWL during HPEs was examined in section 5.4.1. It was found that especially HPEs on five-minute scale were observed during the GWLs WZ, SWZ, BM, TB and TRW, while high daily totals occurred during these GWLs as well, but proportionately to a lesser extent. The influence of the generally high frequency of the GWLs WZ and BM during summer months has already been shown in section 5.4.1. In general At this point, however, the results of this evaluation are to be discussed and brought into comparison with previous studies.

In general the supply of humid Atlantic air in summer from western or northwestern direction inhibits convection and thunderstorms genesis. By contrast, air masses flowing in from the southwest remain relatively warm even in summer and promote heavy rainfall. In contrast, air masses from the north and northeast, as well as an anticyclone over Central Europe are classified as precipitation inhibiting. The GWL HNZ, which is also defined as north is an exception. The main reason for this could be that this GWL is usually accompanied by cold air pools over western or western Central Europe. These cold air masses in the upper air layers involve a high risk of labialization and therefore heavy precipitation. For Central Europe, heavy rainfall is expected in summer during the GWLs TRM and TRW, by the presence of troughs (). However, in the case of the TRM, this could not be established for either of the two classifications. One reason for this could be that the GWL TRM, which often occurs as a so-called “Vb–Wetterlage” rather affects Eastern Germany or Eastern Europe. However, the fact that the TRW is the GWL which most threshold excesses were observed on both time scales was not surprising (within the GWLc). Surprising is the fact that this GWL does not play such a large role in the risk of HPEs within the SVGc. This might be related to the fact of different classification indices of the SVGc and GWLc.

A characterization of the GWLs in terms of temperature and precipitation anomalies for the stations in Potsdam, Prague and Fichtelberg in Central European was published by HOY et al. (2013). Their results for summer half-year have already been summarized in Table 8. They pointed out that heavy precipitation relevant GWLs with eastern (HFA, HFZ, HNFA, and HNFZ) and southern (TRW, SWA, and SWZ) inflow showed an increasing frequency in the summer half year in the period 1901 to 2010. Section 5.4.2 of the present work confirms that HPEs on five-minute time scale are more likely to occur during GWLs with southern and eastern inflow, but also for the GWL HNZ (northern inflow). An increasing frequency of these heavy precipitation-promoting GWLs therefore should carry the danger of more frequent HPEs. However, a significant increase in the period from 1961 to 2015 was only found for the heavy precipitation relevant GWL of the GWLc (+0.2 occurrences per summer season), but not for the SVGc (+0.06). The more objective classification (SVGc) reveals a better understanding and transparency of the heavy precipitation-promoting character of the individual GWLs. Nevertheless, at this point it must be emphatically stated that HPEs caused by convection are not bound to these GWLs. Although these are less to be expected with these GWLs, they are gaining in importance due to the frequency of these GWLs. Otherwise, the finding that the GWLs with western approach (WA, WS, WW, NWA, and NWZ) - with the exception of WZ - and with northern approach (NA, NZ, HNA, HB, TRM, NEA, and NEZ) –with the exception HNZ - in connection with heavy precipitation on a short time scale play a minor role, is verified for both classifications in the present work.

An increase in rainfall relevant GWLs, as found at least for the GWLc, could lead to a more frequent and intensive exposure to HPEs. The results of this study could be an approach, which could explain the results presented here as well as in the studies of MÜLLER & PFISTER (2011), FIENER et al. (2013), and BERG & HAERTER (2011). However, in order to get a truly reliable result, it would take a long time series of higher resolution and higher quality to identify a correlation between heavy rainfall and atmospheric circulation. Until then, working with station data like the one already in place can provide approaches. Linking HPEs to atmospheric circulation patterns is also of great importance in the context of predicting such events and has not yet been delivered to the study area, at least with such high-temporal data for a comparable period of time.

BRIEBER (2018) examined even higher resolved data in minute intervals and came to similar conclusions with regard to heavy precipitation-promoting GWLs. However, there are some differences in methodology and the area of investigation. The fact that summer season is classically defined with the months of June, July and August could explain deviations from the results of this work. Also the study deals with exceedances of percentiles on 15 minute (12 mm) and daily scale (30 mm). With regard to high daily totals, the results of BRIEBER (2018) are very much in line with those of the present work.

Of course, the illustration of the percentage of individual GWLs associated with HPEs provides only a general overview of the whole area. It is important to understand that these statements are not true for every station in this form and that there are regional differences about the effects of GWLs. This is amongst other things is caused by different altitudes of the individual stations. But also the locations of the stations in the windward or leeward area of mountains influence the results. However, it should also be mentioned that measurement errors or data gaps have a considerable influence on the evaluation of the GWLs during HPEs. The reason for this is that the percentage of rarely occurring GWLs is more influenced by extreme events and data gaps than more common GWLs (HOY et al. 2013).

7 Conclusion and Outlook

In the present work, five-minute interval precipitation registrations were evaluated for 19 German stations with sufficient data availability and daily precipitation totals of the same stations. They were analyzed for frequency and intensity trends for the time scales of five minutes, one hour, six hours, and one day in the period from 1961 to 2015 in the summer months May to September. A significant increase was identified for the intensity of the five-minute events for 18 of 19 stations. For the hourly extreme events, however, a significantly increasing trend was only found for individual stations. For the six-hour events none of the stations analyzed show a significant increase in intensity. In some of the stations even a non-significant decreasing tendency could be highlighted. However, for some stations daily precipitation measurements significant increasing intensity and significant decreasing intensity were identified.

Similar results were obtained from the evaluation of the frequency of events on the different time scales. Most of the stations possessed an increasing trend of five-minute events with more equal 5 mm, which spatially tend to be high in the middle of the study area. The longer the time scales the more stations with insignificant increasing or decreasing trends were computed and in one case even for the events with high daily totals a significantly decreasing trend (Saarbrücken) was detected. Also the calculation of the total events with more than 5 mm per 5 minutes brought increasing frequency of +54.6 events per decade, while for the higher time scales of one hour (+10.7) and six hours (+7.3) slightly increasing and slightly decreasing frequencies in daily events (-2.2 events per decade) were striking.

Subsequently, these results were discussed in terms of their validity and compared with the results of other studies. Especially with regard to the improvement of the measurement technology from the 1990s and the unavoidable data gaps, the results have to be considered with reservations. In comparison with other works, however, differences as well as similarities were discovered. The similarities to MÜLLER & PFISTER (2011) and FIENER et al. (2013) who detected increasing intensity and frequency of HPEs on short time scales strengthen the confidence in the results achieved here.

The importance of convective events for the different time scales became visible for the first time in the evaluation of the seasonal cycle of the frequency of HPEs on five-minute and daily scale. While the HPEs of the five-minute time scale piled up where generally the highest temperatures and the highest insolation can be expected (mid-July), a double wave with two maxima at the beginning of June and mid-August was found in the evaluation of the events with high daily totals. Since a strict separation of convective and stratiform precipitation is very complex - even stratiform precipitating circumstances can be accompanied by convective single cells - the role of convection was not excluded for daily events.

In the analysis of the seasonal cycle of the maximum five-minute values of precipitation in the periods 1961-1990 and 1991-2015 distinctively higher values for the later period became visible. This was attributed in large parts to an improvement of the measuring technique starting from in the 1990s, but climatologically relevant changes were not excluded. A similar result also was found in the evaluation of the diurnal cycle of precipitation in both periods. Here, in the period 1991-2015, higher values were found in the maximum five-minute values compared to 1961-1990 averaged over the study area, but due to their distinctive higher level, attributed to the conversion of measurement technology.

Ultimately the heavy rain events that occurred on both time scales were associated with the prevailing atmospheric circulation and - in a further step - particularly heavy precipitation-promoting GWLs were identified. Here, especially the circulation patterns which are characterized by southern or eastern inflow directions but also the GWL with Icelandic High and Trough over Central Europe (HNZ) were found to be particularly heavy precipitation relevant in the five-minute scale. Otherwise, the GWL Low over Central Europe (TM) plays an important role for high daily totals but not for heavy precipitation events in the five-minute scale.

Accordingly, it is recommended to further expand the measurement network in order to develop a better understanding of the heavy rainfall-promoting processes with spatially and temporally high-resolution data. Projects such as the RADOLAN project, which uses spatially high-resolution hourly data since 2001, are an important step towards a better prediction and adaption to heavy precipitation impacts. Admittedly highly resolved data over 18 years are innovative but substantially too short for valid climatological declarations.

8 References

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Declaration of Authorship

Hiermit versichere ich, dass ich die hier vorgelegte Thesis selbstständig und ohne unerlaubte Hilfe angefertigt habe. Zur Erstellung wurden nur die hier aufgeführten Hilfsmittel genutzt. Alle Textstellen, die sinngemäß oder wörtlich aus veröffentlichten Schriften entnommen sind, sowie alle Angaben die auf mündlichen Auskünften beruhen, sind als solche gekennzeichnet.

Bei den durchgeführten und aufgenommen Untersuchungen wurden die Grundsätze guter wissenschaftlicher Praxis, wie sie in der Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis festgelegt sind, eingehalten.

Gemäß § 25, Abs. 6 der Allgemeinen Bestimmungen für modularisierte Studiengänge bin ich mit einer Überprüfung mittels Plagiatssoftware einverstanden.

Datum Unterschrift

Appendix

Station	Date	Δ Lat.	Δ Long.	Δ Altitude	New type
Artern	21.06.1990	0	0	0	NG 200, Droplet counter
	06.09.2006	0	0	0	PLUVIO
Augsburg	08.11.1996	0.05	0.08	-16	PLUVIO
	19.03.1998	0	0.01	1	PLUVIO
	15.12.2006	0	0	-0.6	PLUVIO
Bad Hersfeld	23.06.1961	-0.02	0.01	-4	Hellmann
	21.12.1994	0	0	0	Precipitation sensor after Joss-Tognini, Rocking function
	17.05.2006	0	0	0	PLUVIO
Bad Kissingen	03.06.2004	0	0	0	PLUVIO
	21.12.2004	0.02	-0.01	19.8	PLUVIO
Erfurt	15.02.1995	0	0	2	NG 200, Droplet counter
	09.10.2008	0	0	0	PLUVIO
Fichtelberg	09.10.1990	0	0	0	NG 200, Droplet counter
	29.09.2006	0	0	0	PLUVIO
Frankfurt	01.07.1984	0	-0.01	-1	Hellmann
	25.02.1993	0	0	0	NG 200, Droplet counter
	03.01.2003	0	0	0	PLUVIO
	22.10.2014	-0.08	-0.01	-22.3	PLUVIO
Göttingen	15.12.1967	0.03	0.02	24	Hellmann
	10.11.1993	-0.04	0	-8	Hellmann
	14.06.1994	0	0	0	NG 200, Droplet counter
	24.01.2005	0	0	0	PLUVIO
Hannover	05.11.1964	0	0.02	1	Hellmann
	03.06.1992	0	-0.02	2	NG 200, Droplet counter
	04.08.2008	0	0	0	PLUVIO
Harzgerode	01.05.1977	0.01	0.01	5	Hellmann
	16.06.1992	0	0	0	NG 200, Droplet counter
	22.09.2006	0	0	0	PLUVIO
Kleiner Feldberg	01.10.1992	0	0	0	NG 200, Droplet counter
	10.03.2000	0	0	0	Precipitation sensor after Joss-Tognini, Rocking function
	10.05.2006	0	0	20.6	PLUVIO Precipitation sensor after Joss-Tognini, Rocking function
	06.01.2009	0	0	0	PLUVIO
Lingen	01.09.1990	0	-0.01	1	Hellmann
	02.08.1995	0	0	0	Precipitation sensor after Joss-Tognini, Rocking function
	02.12.2003	0	0	0	PLUVIO
Magdeburg	01.01.1993	0	0	0	NG 200, Droplet counter
	05.04.2006	0	0	0	PLUVIO
Mannheim	14.08.1975	-0.02	0.05	0	Hellmann
	14.07.1993	0	0	0	NG 200, Droplet counter
	15.01.2003	0	0	0	PLUVIO
	31.05.2006	0	0	0.1	PLUVIO
Nürnberg	07.06.1995	0	0	0	NG 200, Droplet counter
	05.12.1995	0.01	-0.03	3.6	NG 200, Droplet counter Precipitation sensor after Joss-Tognini, Rocking function
	19.11.2008	0	0	0	PLUVIO
Oehringen	24.02.1966	0.01	0.01	28	Hellmann
	01.07.1992	0	0	0	NG 200, Droplet counter
	16.05.2006	0	0	0	PLUVIO
Saarbrücken	01.03.1989	0	0	-4	Hellmann
	12.10.1989	-0.01	0	1	Hellmann
	01.08.1996	0	0	0	Precipitation sensor after Joss-Tognini, Rocking function
	15.09.2008	0	0	0	PLUVIO
Trier	13.06.2001	0	0	0	PLUVIO
Weissenburg	14.04.1993	0	0	0	NG 200, Droplet counter
	21.12.2000	0	0	0	PLUVIO
	01.10.2014	-0.01	-0.03	17.3	PLUVIO

Table 10: Changes in measurement location and technology.