Multidecadal trends in the duration of wet spells and associated intensity of precipitation as revealed by a very dense observational German network

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Abstract
Precipitation durations and intensities over the period 1950–2008 are analysed using daily rain gauge data from the Deutsche Wetterdienst raingauge network—one of the densest and most properly maintained precipitation observational networks in Europe. Truncated geometric distribution of the family of discrete distributions was applied for quantifying probability distribution of the durations of wet spells. Further intensities of wet spells of different durations were analysed along with wet spell lengths. During the cold season (October–March) wet periods over the whole of Germany demonstrate a robust pattern of lengthening by about 2–3% for the mean durations of wet spells and up to 6% for extremely long wet periods. This tendency is clearly associated with growing (up to 10% per decade in Eastern Germany) intensity of precipitation during long wet periods (more than 5 days) and the weakening of precipitation events associated with short and moderately long wet periods with both signals being statistically significant. Trends are superimposed with interdecadal variability, which is the strongest in Northern and Central Germany. In the warm season (April–September) there is no robust pan-German trend pattern in the wet spell durations and associated precipitation intensities. Strong structural changes in winter precipitation over Germany potentially imply growing rates of winter ground water recharge over Germany and increasing probability of winter flash and river flooding.

Keywords: extreme precipitation, Germany, trends, wet spells

1. Introduction
Climate variability in the characteristics of Central European precipitation is critically important for understanding the physical mechanisms leading to disastrous floods as well as for the accurate estimation of ground water recharges. Analysis of traditional metrics of precipitation (totals, intensities, number of wet days, absolute and relative precipitation extremes) estimated from European rain gauge records demonstrate a general tendency of increasing mean and heavy precipitation over Central Europe during the last decades (Klein Tank and Können 2003, Schmidli and Frei 2005, Zolina et al 2005, 2009, Grosisman et al 2005, Moberg et al 2006, Alexander et al 2006, Lupikasza et al 2011, Tammets and Jaagus 2013). However, the results depend strongly on the season (Zolina et al 2008, Brien et al 2013). To understand the mechanisms through which changes in mean and extreme precipitation may impact on regional hydroclimate, it is important to
consider durations of wet and dry periods (WPs and DPs) and precipitation intensities associated with wet spells of different durations. Zolina et al (2010, 2013) using daily rain gauge data from European climate assessment and dataset (ECA&D) collection (Klok and Klein Tank 2009) have shown that during recent decades WPs over the whole of Europe experience lengthening with more abundant precipitation extremes being associated with longer wet spells. Furthermore, in some areas lengthening of wet spells was associated with simultaneous increasing of the durations of dry spells, while this signal has different seasonal and regional manifestations (IPCC 2012, 2013, Zolina et al 2013, Serra et al 2013).

Over Central Europe, particularly over Germany, most results of the analysis of wet and dry spell durations as well as of association of longer wet spells with more intense precipitation (Zolina et al 2010, 2013, Serra et al 2013) were quite uncertain, with linear trends not holding robust patterns due to relatively sparse observational density in ECA&D rain gauge collection in this region. Zolina et al (2008) demonstrated that use of a dense observational network may seriously change the conclusions about the tendencies in standard precipitation indices, derived from sparse observational networks (e.g. Klein Tank and Koennen 2003). Uncertainties in estimation of the observed tendencies of the precipitation characteristics make it difficult to effectively validate results on estimation of precipitation structure and extremes from the global and regional climate model simulations for the present and future climate conditions. On the other hand, German territory is heavily affected by flooding with the two major record breaking events being in August 2002 and in June 2013 which resulted in human fatalities and economic losses exceeding billions of Euro (Ulbirch et al 2003). Understanding of the mechanisms of these floods requires detailed regional analysis of precipitation regimes which can be only based on the dense observational network data. In this work 60-year long daily rain gauge records from the operational network of the German weather service (Deutsche Wetterdienst, DWD)—one of the densest and most properly maintained in the world observational precipitation networks—are employed in order to analyse multidecadal tendencies in the duration of wet spells and precipitation intensities associated with WPs of different durations. Focus is given primarily to linear trends. However, their relation to the interdecadal variability will be also discussed.

2. Data and methodology

Daily rain gauge records from DWD network consist currently of 11 617 stations, of which more than 6000 were digitized. Zolina et al (2013) argued that the analysis of the durations of wet and dry spells is very sensitive to the completeness of data records and suggested using only records containing less than 10% of missing data. According to this requirement 3161 stations covering the period from 1950 onwards were selected. The requirement of less than 10% of missing data is somewhat stricter compared to that of Zolina et al (2005) who used records with up to 30% of missing data. However Zolina et al (2005) considered only changes in heavy precipitation, but no attribution about the durations of wet periods was attempted. A selected sub-set of 3161 stations covers Germany with higher station density in Central and Southern Germany compared to the Eastern and Northern parts (figures 1(a) and (b)). A considerably smaller number of rain gauges over Eastern Germany (former German Democratic Republic, DDR) is partly explained by the fact that not all available stations for this area for the period prior to 1989 are already digitized and included in the data base (Zolina et al 2014). Typical station-to-station distance in the Eastern and Northern Germany varies from 10 to 20 km being from 3 to 10 km in densely sampled South and Central Germany. This spatial inhomogeneity of data coverage is, however, consistent with the orography of the region (figure 1(c)) implying a denser network in the areas with complicated orography. Precipitation measurements at DWD network were provided by HELLMANN rain gauges with seasonally activated snow crosses and lids and equipped since 1950s with anti-freezing agents. In the 1990s HELLMANN

Figure 1. Mean climatological duration of WPs (days) for the cold (October–March) (a) and warm (April–September) (b) seasons and the surface topography of Germany (c).
rain gauges started to be replaced by tipping-buckets combined with drop-counting gauges. In the 2000s DWD started to implement automatic weighing gauges (the so-called PLUVIO devices). Further details of the network development, data coverage and observational uncertainties are given in Zolina et al. (2008, 2014).

WP s were quantified as consecutive days with significant precipitation ($\geq 1$ mm d$^{-1}$) that allowed us to account for limited accuracy of measuring light precipitation by DWD gauges (Zolina et al. 2013). Light precipitation, especially snow precipitation is critically exposed to the effect of wind. However, accurate correction of this effect (e.g. Nespor and Sevruk 1999) can hardly be applied to DWD collection, since it requires co-located wind observations which are available only in few locations. Similar threshold was applied in many precipitation studies over Europe and the US (e.g. Brunetti et al. 2004, Groisman et al. 2005 and Alexander et al. 2006).

Over Germany, the results obtained using smaller thresholds (e.g. 0.5 mm d$^{-1}$) are qualitatively consistent with those for 1 mm d$^{-1}$, while in the other regions where national observational practices and data post-processing are less accurate these results may be even quantitatively different. Using the threshold of zero precipitation is unreasonable because this results in considerable lengthening of WPs (and decreasing of associated intensities) on expense of very light precipitation or precipitation traces which are hard to interpret accurately. Estimates of the durations of WPs as well as of the precipitation statistics associated with WPs were performed for the so-called ‘cold season’ (October–March) and ‘warm season’ (April–September) as in Zolina et al. (2013). An alternative approach (based on, e.g. the classical three months seasons), would lead to considerable uncertainties, associated with WPs frequently crossing the seasons.

Following Zolina et al. (2013) truncated geometric distribution (TGD) was applied for the approximation of probability density distribution of WPs and estimation of extremely long wet spells from daily data. TGD belongs to the family of discrete distributions justified by Deni and Jemain (2009) and Deni et al. (2010) for approximation of distributions of wet and dry spell durations. Deni et al. (2010) demonstrated that skills of geometric distribution are comparable to 4–5 other discrete distributions (e.g. Poisson, Polya). Instead of using intensive geometric distribution, Zolina et al. (2013) justified the use of TGD, arguing that durations of WPs and DPs are limited by the duration of record considered and also applying goodness of fit tests. TGD is defined on the interval of the length of the record (6 months in our case) and represents a transform of a standard one-parametric discrete geometric distribution on the interval $[1, \infty]$. Details of application of TGD and estimation of the parameters are given in Zolina et al. (2013). Application of TGD allows for estimation of the durations of WPs of rare occurrence (e.g. corresponding to 95th or 99th percentiles) which can be hardly estimated for the raw data given a typical number of WPs per season of less than 30. Additionally the extension of TGD to the fractional truncated geometric distribution (FTGD) was applied in this study. This distribution eliminates the impact of changing number of wet and dry days from year to year on the statistics of the durations of wet spells and dry spells and allows one to discriminate the effect of changing number of wet days and of the regrouping of wet days into spells of different durations (Zolina et al. 2013). For every WP mean precipitation intensity and maximum precipitation were also estimated. Along with the statistics of the durations of WPs these allow for intensity-duration analysis of changes in precipitation regimes.

3. Results

3.1. Climatology of the durations of wet spells

Figure 1 demonstrates for the reference seasonal climatological distributions of the mean durations of WPs. Climatologies of the durations of wet periods for the cold and warm seasons (figures 1(a) and (b)) show that winter WP durations range from 2 to 3.5 days in most regions with summer durations being on average from 1.6 to 3 days. Eastern Germany during both seasons is characterized by shorter WPs than the Western Germany with 1-day WPs contributing typically around 50% of all rain events. The longest WPs are closely associated with the mountain ranges (figure 1(c)) in both seasons. Even not very high systems such as Siebengebirge, Harz, Thuringen Wald, Eifel, Ebbengebirge (most are less than 600 m) are clearly associated with highly localized maxima of the durations of WPs. Similarly, locally long WPs of more than 3 days in winter and more than 2.5 days in summer are observed in the regions of Bavarian Alps, Schwarzwald and Schwaebische Alb along the German southern border that might be associated with the advection of moist warm air from the Mediterranean basin. Another region characterized by somewhat longer than average WPs is the Northwestern part of Lower Saxony and Schleswig-Holstein where precipitation regimes are largely influenced by the coastal processes associated with the prolonged rain episodes in both seasons.

Extremely long WPs were quantified by the 95th percentile of the TGD. This estimate corresponds to the minimum duration which has 5% of the longest WPs. Figure 2 shows that WPs corresponding to the 95th percentile of TGD range from 5 to 14 days in cold season with the longest wet spells (up to 15 days) being observed in the southern

![Figure 2](image-url)
3.2. Linear trends and multidecadal variability in the mean and extremely long durations of wet spells

Linear trends in the duration of WPs over the last 60 years were estimated using least squares with statistical significance of trend estimates quantified using the non-parametric Mann–Kendall test. Additionally for the whole of Germany and individual large regions, there has been estimated field significance (Livesey and Chen 1983, Wilks 2006). Field significance estimates quantify the required number of passes of single tests (the number of individual locations with locally significant trends) necessary to ensure the overall significance of the trend pattern for a region. Figures 3(a) and (b) shows estimates of linear trends in the mean durations of WPs for the cold and warm seasons. During the cold season the mean duration of WPs experience increase from 2 to more than 5% per decade which is equivalent to 0.3 to more than 1 day during the 60-yr period. The strongest upward trends in the

![Figure 3](image-url)
mean duration of WPs are observed in Northern Germany over Schleswig-Holstein, lower saxony and in Bavaria where the strongest increase amounts to 6% per decade and more than 85% of stations report statistically significant positive trends implying field significance at 99% level. Estimates of field significance show that for the whole of Germany, robust upward tendency in the mean duration of WPs in winter is confirmed at 95%. During the warm season, trends in the durations of WPs (figure 3(b)) do not form any robust pattern with the locations of positive tendencies in WP duration being superimposed by the locations showing shortening of WPs over the last 60 years. The magnitude of both positive and negative trends in the durations of WPs is twice as small compared to those for the winter season (the largest trend estimates are smaller than 3% per decade). Tests of the field significance for the whole of Germany as well as for individual large regions show that during summer neither area holds field significance for either positive or negative trends in the mean duration of WPs.

Patterns of trends in the durations of extremely long WPs (95th percentile) generally follow to those for the mean durations of WPs (figures 3(c) and (d)). During the cold season there is an overall pattern of growing occurrence of extremely long WPs implying field significance at 98% level. The strongest increase of the 95th percentile of the durations of wet spells with magnitudes exceeding 6% per decade (from 3 to 4.5 days during 60 years) is observed over the North Sea coast, over Hessen and Southern Thuringia and over Southern Bavaria where the maximum increase amounts to more than 10% per decade (i.e. 7 days over 60 days). Summer trends in the durations of extremely long WPs (figure 3(d)) do not show a robust pan-German pattern with trends of different sign being superimposed with each other. Regionally, the shortening of summer WPs is observed in Southern Bavaria (−2 to −5% per decade) and the lengthening of about 2–4% per decade is identified in Southern Baden Wuerttemberg as well as in Eastern Nordrhein-Westfalen and Rheinland-Pfalz. However, these regional patterns are not statistically significant.

Linear tendencies in the duration of WPs during recent decades may be largely superimposed with decadal-scale and multidecadal variability. Figure 4 shows regional time series of the duration of mean WPs averaged for the three large regions. In winter (figure 4(a)) the persistent upward tendency in the duration of WPs over the whole 60-yr period is observed only in South Bavaria. On the other hand, a positive linear trend signal is evident only before the 1990s in Northeastern and Central Western Germany, while during the last two decades there is a weak tendency towards shortening of WPs associated with interdecadal changes. In summer (figure 4(b)) interdecadal variability dominates over linear changes in Central Western Germany, showing shortening of WPs from the 1950s to 1980s and lengthening of WPs from the 1980s to 2000s.

3.3. Association of changes in the duration and intensity of wet periods

It is interesting to consider now whether the changes in the duration of wet spells are coordinated with changing intensity of precipitation associated with wet episodes of a given duration. Zolina et al (2010) using ECA&D rain gauge collection (Klok and Klein Tank 2009) reported that growing duration of WPs was associated with increasing intensity of rainfall during longer wet spells and the weakening rain intensity of the short WPs, while the robustness of this phenomenon for Germany and some other Central European
regions was not proven due to limited number of observations used for the analysis. Figures 5(a)–(c) shows winter linear trends in the fractional contribution of precipitation during WPs of different durations to the seasonal total. Remarkably, in winter the contribution from short and moderately long WPs has declined by 2–5% per decade during the last 60 years, while the contribution from relatively long WPs increased by more than 6–8% per decade with the strongest tendency in Northwestern Germany, especially in the coastal regions of the North Sea. This increase is consistent with the strongly intensified precipitation of long WPs in winter shown in figure 6(a). Statistically significant positive trends in the mean intensity of precipitation associated with long WPs amount to more than 4% per decade over most of Germany. This implies increase of the intensity averaged over the long WPs by 2.9–3.6 mm d$^{-1}$ during 60 years. Interestingly, the largest increase of the precipitation intensity associated with long WPs is observed over Eastern Germany where the trends in the occurrence of extremely long WPs, although significantly positive, are somewhat weaker compared to Western Germany regions. Thus, over Eastern Germany winter trends in the fractional contribution of precipitation during long wet spells to the seasonal total are largely provided by intensified rainfall rather then the lengthening of wet spells.

During the warm season (figures 5(d)–(f)) fractional contribution of precipitation associated with long WPs to the seasonal total is increasing (more than 2% per decade) over Baden-Wuerttemberg and Eastern Germany and shows primarily negative trends (of about 1.5–2.5% per decade) in Central Germany. These regional signals are quite consistent with the tendencies in the intensity of precipitation during long WPs (figure 6(b)). However, in summer both positive and negative tendencies in the intensities of precipitation during long WPs do not hold field significance. This holds for the whole of Germany and for the selected regions.

In order to jointly consider changes in the durations and mean intensity of WPs over different regions two-dimensional duration-intensity distributions were analysed. They were first introduced in engineering hydrology and applied for climate analyses by Zolina et al (2010). Figures 7(a)–(c) shows estimates of linear trends in the occurrences of precipitation intensities associated with different durations of WPs on the plane of two-dimensional probability distribution of the durations and intensity of WPs. These diagrams are shown for three regions—Northwestern Germany close to the North Sea coast, Central Western Germany and Southern Bavaria. The results
Figure 7. Estimates of linear trends (% per decade) in the frequency of WPs of different duration and mean intensities for the three regions of Germany (shown in inlay maps) for cold (October–March) season. Bold sided squares mark trends significant at the 95% level (Mann–Kendall test). Blue contours show precipitation totals for WPs of different durations and mean intensities.

are shown only for the winter season for which our previous analysis identified a clear intensification of the mean intensities of long WPs. All three regions demonstrate a clear tendency of increasing precipitation intensity for WPs longer than five days and simultaneous decreasing of the intensity of rainfalls during short WPs. Remarkably for all regions the occurrence of heavy rainfall (mean intensity is more than 16–20 mm d\(^{-1}\)) has decreased for short WPs (less than 3 days) by more than 10% per decade. Upward tendencies in the precipitation intensity associated with long WPs amount to more than 15% per decade. Similar analysis performed for extreme precipitation (no figure shown) clearly replicates the pattern drawn for the mean precipitation with even stronger magnitude and a higher significance of the trends. Analysis of trends in the coordinates ‘intensity-duration’ for summer season (not shown) does not reveal any significant trend patterns that was predicted by previous analyses (see, e.g. figures 3–5).

4. Summary and discussion

Our analysis based on one of the densest regional precipitation networks in Europe shows that over Germany there is a robust tendency of lengthening of WPs during the cold season with linear trends being up to one day during the last 60 years for the mean durations of wet spells and exceeding regionally five days over 60-year period for extremely long WPs. This pan-German winter tendency hinting on considerable change in the structure of Central European precipitation, is clearly associated with the growing intensity of precipitation during longer WPs and decreasing intensity of rainfalls during short and moderately long WPs. If in the 1950s and 1960s only up to 29% of the cold season precipitation totals were formed by relatively long wet spells, during the decades of the 1990s and 2000s this fraction has increased to 37%. A very robust signal, however, is explored for the cold season only. In the warm period linear trends in the duration of wet spells over Germany do not form any robust pattern and exhibit mostly a noisy superposition of trends of the opposite sign with no region holding field significance.

Our results based on more than 3000 stations demonstrate that the lengthening of wet spells and association of more abundant rainfalls with prolonged rain episodes found over most of Europe from a sparse ECA&D data (Zolina et al 2010) is clearly a winter phenomenon over Germany. Earlier analyses demonstrated that there is a clear seasonality in the mean and extreme precipitation over Germany (Zolina et al 2008, 2013, Schlünzen et al 2010, Brienen et al 2013), however seasonally dependent changes in precipitation structure (Zolina et al 2013, Serra et al 2013) were quite uncertain. Our results are consistent with the analyses for adjacent areas, like the Northern Swiss where Schmidli and Frei (2005) found pronounced tendency in the length of the wet spells in winter, while in spring and in summer the heavy precipitation and the spell-duration statistics did not show statistically significant trends. Similarly, Zolina et al (2013) demonstrated a clear upward tendency in the duration of WPs over The Netherlands (where station density is comparable to that over Germany) in both winter and summer season. Our results for Northwestern Germany are very consistent with this finding in winter and also show a regional pattern of growing durations of WPs (2–2.5% per decade) in summer over western parts of Niedersachsen and Nordrhein-Westfalen. This summer pattern over both The Netherlands and Northwestern Germany is likely associated with the interaction of atmospheric flow with the coasts resulting in highly variable in space and time convective precipitation.

Our findings provide an interesting framework for validating the results of global and regional climate model simulations. Climate models typically consider changes in the mean and extreme precipitation with no attention to the synoptic structure of WPs and DPs. For instance, Tomassini and Jacob (2009) demonstrated consistency of the changes in precipitation extremes simulated by the regional REMO model with
signals revealed by DWD stations over Germany. However, it is unclear whether regional climate models can accurately replicate the structure of synoptic WPs. An important avenue for the further development of this study is the analysis of physical mechanisms associated with the observed changes in the durations and intensity of WPs. Although intuitively winter season lengthening in the durations and intensity of wet spells should be associated with changes in cyclone activity, changes in cyclone counts may not necessarily explain this signal. For instance, analysis of cyclone tracks in modern era reanalyses (e.g. Tilinina et al 2013) does not demonstrate robust trends in the number of cyclones over Central Europe. To associate the cyclone activity with prolonged rain episodes one needs to either consider serial clustering of cyclones (Pinto et al 2013) or to analyse specific conditions within cyclone systems leading to the persistent precipitation (Päädäm and Post 2011). These mechanisms need to be considered in view of large-scale changes in the atmospheric circulation, especially in summer (Boe et al 2009) that may include also the analysis of different weather types associated with prolonged wet and dry episodes. Equally important is to analyse changes in the duration and intensity of WPs in the model simulations of the future climate conditions. Future climate projections show minor changes in cyclone activity compared to the present climate conditions (e.g. Löptien et al 2008, Champion et al 2011), however, the same projections report increasing intensity of mean and extreme precipitation (e.g. Champion et al 2011). Of special interest will be further analysis of the decadal-scale and interdecadal variability in the duration and associated intensities of WPs—an important issue which was only marginally considered in this study. This may provide interesting links to the oscillatory climate modes such as North Atlantic Oscillation (NAO) and Atlantic Multidecadal Variability (AMV), potentially driving cyclone behaviour and atmospheric moisture transports in the Atlantic–European Sector. Further analysis of potential mechanisms associated with changes in the durations and intensities of WPs will benefit from consideration of changes in the magnitudes of intraseasonal variability of these variables (IPCC 2012).

Changing structure of Central European precipitation may have serious implications for understanding the mechanisms of disastrous flash and river floods and for the water management. For instance, Petrow and Merz (2009) argue for increasing intensity of the winter floods in the catchment areas of Rhine and Weser, where strong trends in the durations of WPs and associated rainfall intensity are observed. Impact of the lengthening of WPs on ground water recharge may seriously change ground water levels and potentially affect also the ground water quality (Ng et al 2009, 2010). For the accurate analysis of these phenomena of a special interest would be to consider the responses of ground water to structural changes in precipitation using state-of-the-art hydrological models (Maxwell and Kollet 2008).

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