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High spatial and temporal organisation of changes in precipitation over Germany for 1951-2006

Short title
Changes in precipitation over Germany for 1951-2006

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Abstract
Temporal changes in daily precipitation observed at more than 2300 stations in Germany during the second half of the 20th century are analysed. Compared to other studies, this analysis is based on a very high spatial density of observation locations and complete areal coverage of Germany. Changes in four precipitation characteristics are investigated: (1) total amount of seasonal and monthly precipitation, (2) mean and 95%-quantile (q95) of daily precipitation, (3) transition probabilities to quantify wet and dry spells, and (4) precipitation amounts for a 7-day event with return period 100 years. For all parameters strikingly clear trend patterns in space and time (of the year) emerged. Stations with increasing and decreasing trends are never found in direct neighbourhood, but are well separated from each other. Changes are season- and even month-specific. These clear spatial and temporal patterns are an expression of the organisation of precipitation mechanisms over Germany. These findings add a note of caution in regard to trend analyses: Spatially and temporally aggregated trend studies might not disclose the complete range of changes and might miss important details. Interestingly, the variability of daily precipitation has changed in parallel with the mean behaviour: Those regions and seasons that show an increase in mean show also an increase in standard deviation, leading to a disproportional increase in heavy precipitation. In addition, there is a tendency towards higher persistence, in particular, longer wet spells in winter, spring and autumn, and longer dry spells in summer. If these trends continue, there will be an increasing potential for floods in winter and spring, and increasing problems for water availability in summer in regions that show signs of water stress today.

1 Introduction
Precipitation is one of the most important climate variables. Given the link between temperature and atmospheric water holding capacity, human-induced global warming may already have contributed to changes in precipitation. Changes in extreme precipitation are of particular importance in this respect, and it has been suggested that heavy-precipitation events increase with global warming (Trenberth et al., 2007, Min et al., 2011). Against this background, we analyse changes in daily precipitation over Germany during the second half of the 20th century.
Much effort has been spent on detecting trends in precipitation, and in particular, in extreme precipitation, as this can have adverse consequences for society. For

Europe, most analyses of observed precipitation found increasing heavy precipitation during the period of extensive data coverage, i.e. from several decades to the last century (Klein Tank and Koennen, 2003, Groisman et al., 2005, Alexander et al., 2006, Moberg et al., 2006, Zolina et al., 2005, 2008, Zolina, 2014). For example, Moberg et al. (2006) investigated changes in precipitation extremes derived from daily time series for Europe west of 60° E for 1901-2000. They found that winter precipitation totals have increased by approx. 12% with similar trends in some percentiles (90^{th}, 95^{th}, 98^{th}) of daily winter precipitation (analysed on 121 stations north of 40°N). For summer they did not find significant trends over the whole area under investigation, but a slight tendency towards more intense but less frequent precipitation. Zolina et al. (2010) analysed the duration of wet spells in Europe over the period 1950-2008 using daily data from 699 rain gauges. They found that wet periods, defined as consecutive days with significant precipitation (more than 1 mm), have become longer by about 15-20%. Interestingly, the total number of wet days has not increased, pointing to a change in the structure of rainfall events. Moreover, heavy precipitation events have become more intense. A similar study of Zolina et al. (2013) using data for 1950-2009 specified that the changes found in the previous work have mainly occurred in winter. Pauling and Paeth (2007) investigated the changes in winter precipitation anomalies over Europe back to 1700. They found that over Central Europe wet winters were more frequent during 1951-2000 with respect to the past 300 years (except 1701-1750). For Germany, Troemel and Schoenwiese (2007) analysed 132 time series of monthly total precipitation covering 1901-2000. For most of the year, they found an increasing probability of exceeding the 95^{th} percentile and a decreasing probability of falling under the 5^{th} percentile for several stations in the south of Germany. The same results were found for the western part of Germany for summer. In winter, both probabilities increased in the west of Germany. The opposite development was found for the east of Germany in summer and autumn (decrease in both probabilities: exceeding the 95^{th} and falling below the 5^{th} percentile). Hence, this study illustrated the large heterogeneity of precipitation behaviour in space and in the annual course, and pointed to the importance of region- and season- or even month-specific analyses. Zolina et al. (2008) analysed a much denser network of stations (>2000) for the period 1950-2004. They analysed linear trends in extreme and heavy precipitation. As indicator they used the 95% and 99% percentiles of the gamma distribution fitted to daily precipitation values. Regrettably their analysis was limited to the western and southern parts of Germany. They found positive linear tendencies in heavy precipitation for all seasons except summer where most trends were negative and emphasized the importance of seasonal analysis, since their trend analyses without seasonal breakdown did not show any clear spatial patterns. A subsequent study by Zolina (2014) analysed wet spells over the whole of Germany at 3161 stations for

1950-2008, but was restricted to only two seasons. Similar results were found by Hundecha and Bardossy (2005) who analysed the evolution of daily extreme precipitation for 1958-2001 in the German parts of the Rhine basin using data of 611 precipitation stations. For the area of east-central Germany, Haensel et al. (2009) studied trends of monthly rainfall for 1951-2006 based on more than 200 precipitation stations. They found season-specific trends with increasing monthly winter precipitation and decreasing summer precipitation. Although the trend patterns showed similarities across the region, the winter increase was highest in the mountainous south-western part, whereas the summer decrease was most pronounced in the northern lowland. For the same period (1951-2006), Lupikasza et al. (2011) analysed extreme precipitation trends for east-central Germany and southern Poland. They used different indicators based on daily precipitation data at 43 stations for the complete area. For all seasons and for east-central Germany, increasing trends dominated the temporal changes, however, increases were particularly significant in winter.

Although several studies (see Table 1 for an overview) have analysed the time development of precipitation for Germany, they either used data of sparse observational networks, or analysed only parts of Germany and/or restricted themselves to a very limited choice of precipitation variables that mainly aim at quantifying extremes. In this paper, we complement this knowledge by analysing changes in four indicators that describe precipitation characteristics quite extensively: (1) the total amount of seasonal and monthly precipitation, respectively, (2) the mean and 95%-quantiles (q95) of daily precipitation, (3) transition probabilities to quantify wet and dry spells, and (4) precipitation amounts for an extreme event of 7 days with return period 100 years. All analyses are performed on a seasonal or even monthly level and are based on data of more than 2300 precipitation gauges covering the whole area of Germany for the period 1951-2006. Thus an extended analysis of precipitation on an exceptionally good and homogenous data base is provided.

The analysis of changes in multi-day, extreme precipitation is of particular interest. Floods are associated with different time scales of the triggering rainfall events. Trans-national and trans-basin floods are typically related to multi-day, heavy precipitation events. The most recent examples are the August 2002 and June 2013 floods in Central Europe. The flood in 2002 has been the most expensive natural disaster in Germany so far, and the 2013 flood has been the most severe flood – in hydrological terms – in Germany since 1951 (Schröter et al., 2015). Each event caused damages in the order of 10 billion EURO for Germany alone (Merz et al., 2014). It is important to understand whether the probability of precipitation events with the potential to trigger large-scale floods has changed in the past decades.

2 Data

The data used in this study were mainly derived from the precipitation gauge network of the German Weather Service (DWD) and processed by the Potsdam-Institute for Climate Impact Research (PIK). Data processing by Oesterle et al. (2006) included the selection of 2342 stations with continuous records in the period 1951-2006 and quality control of the data. Precipitation was monitored at all stations, 270 stations also recorded other climate variables, such as air temperature (daily minimum, maximum and mean) and wind speed. These variables were interpolated to the precipitation gauge stations, such that a complete set of meteorological variables exists for each of the 2342 stations. Quality control of the data covered checking for physically meaningful values, consistency of air temperatures, plausibility of sequences with identical values, and spatially inconsistent measurements. Erroneous and missing values were filled with the help of correlated neighbouring stations. The data processing is described in detail in Oesterle et al. (2006). The resulting gap-free data set of 2342 stations located in and near Germany (Figure 1) and covering the period 1951-2006 in daily time steps was available for this study. Other studies such as Zolina et al. (2014) allowed gaps of up to 10% in their data which allowed the use of even a greater number of stations. Nevertheless, their Figure 1 illustrates nicely that the time span analysed here covers the period with the densest and most complete (in terms of data gaps) network of precipitation stations in Germany – the number of stations was considerably less before 1951 and decreased drastically again in the beginning of the 2000s.

Snowfall has a larger wind drift undercatch error than rainfall for the Hellmann gauges used in Germany. Hence, higher winter temperatures and associated redistribution from snowfall to rainfall could wrongly be interpreted as increasing winter precipitation (Forland and Hanssen-Bauer, 2000). To avoid this misinterpretation, undercatch errors were corrected considering wind speed and aggregation state as proposed by Yang et al. (1999).

Most of the parameters were analysed on a seasonal basis. Statements referring to ’winter’ include January and February of the particular year and December of the previous year. This means that the seasonal analyses contain time series from December 1951 to November 2006. 'Winter' (WIN) always refers to December, January, February, 'spring' (SPR) to March, April, May, 'summer' (SUM) to June, July, August, and 'autumn' (AUT) to September, October, November.

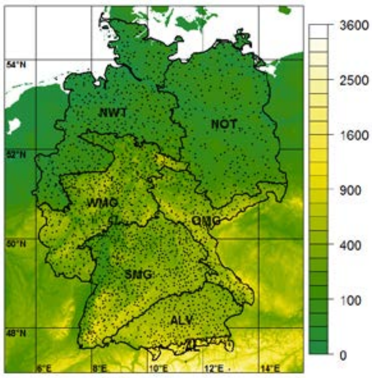

Figure 1. Map of Germany including elevation (in m a.s.l.) and locations of precipitation gauges (dots). Bold lines show the regional sub-division into landscapes (abbreviations given in section 3.3) with similar climate, geomorphology and topography.

3 Methods

3.1 Threshold between wet and dry days

A distinction between 'precipitation' and 'no precipitation' (or 'wet' and 'dry') days is necessary to derive transition probabilities and to fit probability density functions (pdf) to the precipitation data. The threshold between these two states was set to 0.5 mm, i.e. only days with precipitation larger or equal to 0.5 mm were considered as wet days. Days with less than 0.5 mm were defined as 'dry' for transition probabilities and were not used when fitting the pdf. This threshold of 0.5 mm (as in Kundzewicz et al., 2006 and Groisman et al., 2005) was established to avoid that measurement errors were taken as rain and to ignore amounts of precipitation that were not discernible and not meteorologically relevant.

To quantify the amount of light precipitation which we neglected in our analyses, the mean annual amount of precipitation contributed by events of less than 0.5 mm day^{-1} was examined. The average amount of light precipitation is around 7 mm year^{-1} with up to 14 mm year^{-1} in very few places in the northern half of Germany and less than 4 mm year^{-1} at some stations in the south of Germany. Monthly mean light precipitation was always less than 2 mm, averaging around 0.6 mm. Hence, we conclude that the contribution of light precipitation to the total amount of precipitation is negligible even for those parts in the east of Germany with annual precipitation of less than 600 mm.

3.2 Derivation of time series of precipitation characteristics

Total Precipitation

Seasonal and monthly precipitation totals were analysed. The total precipitation of a particular time period is the sum of all precipitation values within this time period without any distinction between 'precipitation' and 'no precipitation'.

Mean, variability and heavy precipitation indicators for daily precipitation

For each station, a probability density function of daily precipitation amount was derived by fitting a Gamma pdf to the observations (only days with precipitation ≥ 0.5 mm) of each season and year. The Gamma distribution is typically used for describing daily precipitation amounts (e.g. Wilks and Wilby, 1999, Furrer and Katz, 2007). We calculated the mean and standard deviation (sd) of the data and derived the shape and scale of the Gamma pdf by:

$shape = mean^2 / sd^2; scale = sd^2 / mean$.

Finally, the 95% quantile (q95) was obtained from the fitted pdf. The time series of mean, standard deviation (not shown here) and upper quantile were further analysed for trends on a seasonal level.

Heavy precipitation indicators (e.g. q95) can be derived from fitted Gamma-pdf (e.g. Groisman et al., 1999, Zolina et al., 2005, 2008) or directly from the empirical distribution (e.g. Hundecha and Bardossy, 2005, Brienen et al., 2013). Zolina et al. (2005) compared both approaches and concluded that the Gamma-distribution-based indices were more robust to sampling uncertainty. Another advantage of the distribution-based approach is that the fitted distributions can be used to derive multi-day precipitation indicators.

It has been shown that the Gamma distribution may not well represent the upper tail of observational data (Panorska et al., 2007, Furrer and Katz, 2008). Hundecha et al. (2009) used a mixture of Gamma and generalized Pareto distributions with dynamically varying weights and obtained a much better representation of daily precipitation variability. However, due to the large number of fitting parameters, such an approach is not feasible in our application which is based on samples of approximately 37 values (average number of wet days per season).

To check the suitability of the Gamma distribution, we applied the Kolmogorov-Smirnov test (Marsaglia et al., 2003) with significance level $\alpha = 0.1$ to every sample to which the Gamma pdf was fitted. For the large majority of stations and seasons the test revealed no significant difference between the data and the fitted pdf. The number of samples (i.e. years) that were not well represented by the Gamma pdf were counted for each station and season. If a station had less than 40 (out of 55) years that could reasonably be described by the Gamma distribution in a particular season, no trend test was performed and hence no trend would be detected. In total, 12 stations were eliminated in winter, 27 in spring, 50 in summer and 18 in autumn, i.e. between 0.5 and 2.1% of the stations were eliminated. Most of them were situated in central-east Germany (northern part of region OMG – East Central Uplands, see section 3.3 for abbreviations) and, especially for summer, in the region NOT – Northeast German Plain.

Transition probabilities

The occurrence of precipitation, or the absence of precipitation, is not completely random over time. Due to the tendency for persistence at the daily time scale, the occurrence of wet or dry spells (periods of consecutive days with or without rain) is likely. This characteristic is frequently described by a two-state, first-order Markov model with two states (1: wet day, i.e. precipitation ≥ 0.5 mm; 0: dry day, i.e. precipitation < 0.5 mm). The occurrence of precipitation is modelled as a binary-valued discrete random variable (Wilks and Wilby, 1999). The transition probabilities of all possible transitions between dry and wet are given as: P_{00} – dry day is followed by another dry day; P_{01} – dry day is followed by wet day; P_{10} – wet day is followed by dry day; P_{11} – wet day is followed by another wet day. There are only two possibilities for the state of day t+1. Therefore, the probabilities of two complementary transitions add up to 1: $P_{00} + P_{01} = 1; P_{10} + P_{11} = 1$, so only transitions P_{00} and P_{11} are examined. These probabilities were derived from the observed daily time series by calculating the relative frequency of each transition of each season and year.

Multi-day precipitation amount of given return period

Changes in the probability density function of daily precipitation and in the transition probabilities may lead to changes in the exceedance probability of extreme events with duration longer than one day. To investigate changes in such extreme, multi-day precipitation events, time series of precipitation amount for selected multi-day precipitation events and selected return periods were derived for each station and tested for trends. In this way, the joint effect of temporal changes in the pdf and in the transition probabilities could be assessed. The following Monte Carlo procedure is set up for each season and year and given station:

1. By randomly drawing from the transition probabilities P_{00} and P_{11} derived from the observations, a new time series of wet and dry days is created (90 days for a season).
2. Precipitation amounts are randomly drawn from the Gamma pdf fitted to the station data for each season and year, and assigned to 'wet' days of step 1. In this way, a synthetic daily precipitation time series is generated for the period 1951-2006.
3. The maximum precipitation amount occurring within n consecutive days is selected.
4. By repeating steps 1-3 10,000 times, 10,000 synthetic times series of maximum n-day precipitation are derived.
5. A generalised extreme value distribution (GEV) is fitted to these 10,000 values, and the precipitation amount corresponding to a given return period is derived. For each season and station, this results in one time series of n-day, m-year return period precipitation amount. The assessment of multi-day

precipitation was performed only for stations that passed the Kolmogorov-Smirnov test in at least 40 years out of 55 (for number of stations being removed, see section 3.2).

3.3 Trend analyses under consideration of temporal and spatial correlation

Trends were analysed by means of the non-parametric Mann-Kendall trend test which calculates a rank correlation coefficient (Kendall, 1938). Trends were judged to be significant if the associated two-sided p-value was less or equal to 0.1 (significance level 10%). The Mann-Kendall trend test was applied to time series of annual values of the respective parameters. For example, trends in the 95%-quantile of daily summer precipitation were based on, firstly, estimating the 95%-quantile for each year given the daily precipitation values ≥ 0.5 mm of this year's summer, and secondly, analysing the resulting time series of annual values of the 95%-quantile.

To quantify the magnitude of change, the slope of the trend was calculated using the non-parametric trend slope estimator proposed by Sen (1968):

$$\beta = M\left[\frac{x_j - x_i}{j-i}\right]; \text{ for all } j > i;\ x_j, x_i = \text{respective parameter in years } j, i.$$

Since persistence in the time series may distort the results of the Mann-Kendall trend test, all (annual) time series were checked for autocorrelation. Most of them were free of any autocorrelation but a few showed significant correlation at some time lags. To account for the bias in trend results for autocorrelated time series, a block bootstrap approach as proposed by Khaliq et al. (2009) was used. The underlying idea is to resample the autocorrelated time series in a way that preserves the correlation structure. Then the test statistic is obtained from the resampled time series. By doing this for a large number of times (10,000), a simulated distribution of the test statistic was obtained. If the test statistic of the original time series lies in the tails of the simulated distribution – i.e. it is unlikely to get the same test result from a time series that contains a similar autocorrelation structure as the original series but no temporal trend – the test result of the original time series is judged to be unaffected by autocorrelation. To preserve the autocorrelation structure while resampling, the resampling is done in blocks of determined length. Following the approach of Khaliq et al. (2009), the block length is the number of significant (at significance level $\alpha = 0.1$) contiguous serial correlations plus 1. The Block Bootstrap approach was employed on Kendall's tau statistic for time series that showed an apparently significant trend. Only if the result of the Block Bootstrap approach confirmed the presence of a trend this was considered to be justified.

The results of our trend analyses show spatial clustering of stations with significant trends. Obviously, neighbouring stations may experience similar changes in rainfall characteristics and thus a station is likely to show a trend if the neighbouring station does. In trend detection studies with many sites within a region, it is advisable to evaluate the field significance, i.e. the significance of trends across the region. This is done by comparing the number of observed significant trends with the number expected within the region. It has been found that spatial correlation between sites may inflate the results of trend tests (Douglas et al., 2000). Hence, we apply the field significance test as given in Yue et al. (2003). This test accounts for spatial correlation by a bootstrapping procedure which preserves the cross-correlation among sites. Field significance was calculated for 7 regions in Germany. The spatial extent of these regions is given in figure 1 and was chosen according to the Federal Agency of Nature Conservation (BfN). These regions represent landscapes with similarities in climate, geomorphology and topography. The abbreviations used in figure 1 and in the following are: AL – Alps, ALV – Alpine Foreland, NOT – Northeast German Plain, NWT – Northwest German Plain, OMG – East Central Uplands, SMG – Southwest Uplands/Scarplands, WMG – West Central Uplands.

3.4 Visualisation of results

All trend analyses are performed directly on station data. To better visualise the findings, the results obtained at every station are interpolated to a grid covering Germany by means of inverse distance interpolation. This kind of visualisation is useful to show spatial characteristics of average values for transition probabilities and multi-day precipitation. For the display of trend results the magnitude of trends (absolute change derived from Sen's slope over the study period) is interpolated to the whole area. Stations with significant trends are marked with dots.

4 Results and discussion

4.1 Changes in total precipitation

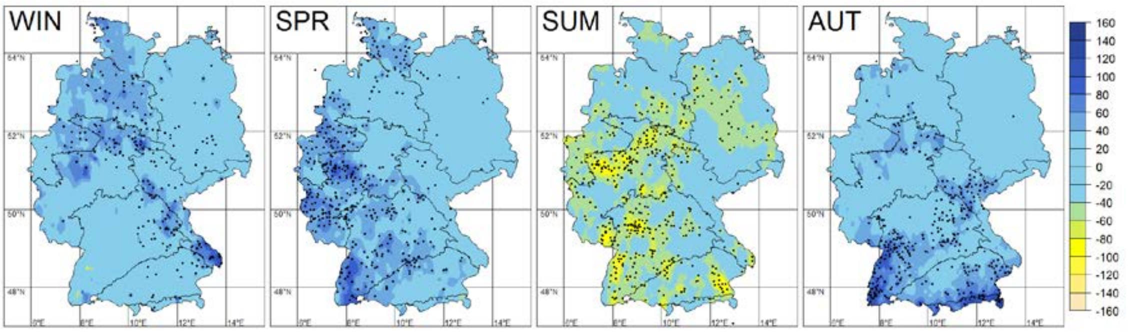

Figure 2. Change of seasonal total precipitation (in mm per season for 1952-2006). Dots indicate stations with significant trend (α = 0.1) in the respective season. The background is coloured according to interpolated values of the magnitude of trends at all stations (derived from Sen's slope). Black lines show the regional sub-division into landscapes as given in figure 1.

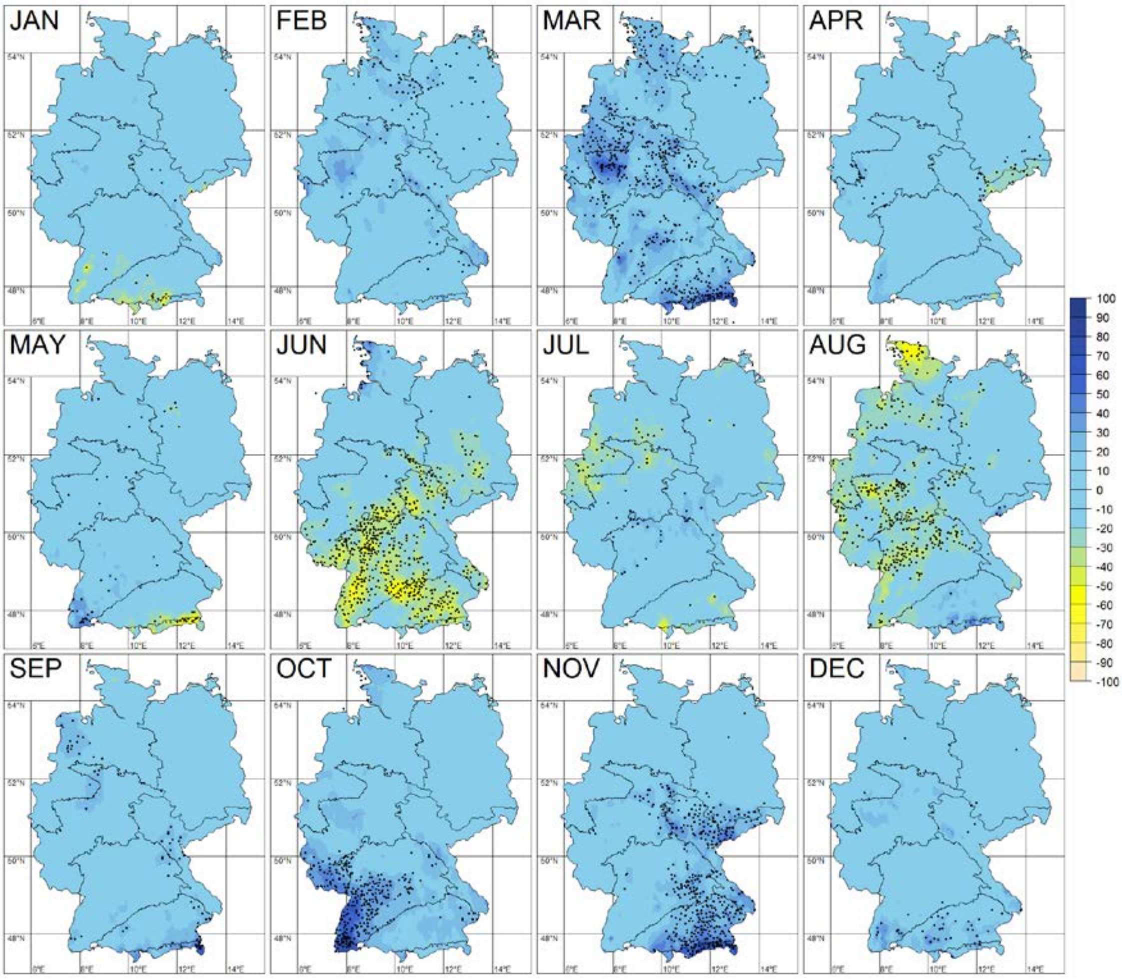

Figure 3. Change of monthly total precipitation (in mm per month for 1951-2006). Plot as in figure 2.

When applying the Mann-Kendall trend test to time series of monthly and seasonal precipitation, very distinct patterns emerge (figures 2 and 3). Most obvious is that all seasons except summer show almost only positive trends, i.e. trends towards higher precipitation. Table 2 gives the number of stations showing trends in seasonal and monthly total precipitation. Winter precipitation increased significantly in the Northwest German Plain and East Central Uplands. Many stations experienced a total increase of winter precipitation of 40-80 mm (i.e. 10-30%, in some places 40%), others, especially in the east of Germany, showed a total increase of less than 40 mm (around 20%). Spring precipitation increased significantly in western regions (NWT, WMG, SMG) with a magnitude of 20-60 mm (i.e. 10-30%) and a higher increase in mountainous regions of the Black Forest and the Sauerland. Summer precipitation showed a distinct decrease of 20-100 mm (10-30%) in many parts of Germany with field significance being observed for regions ALV, NOT, SMG, and WMG. In some places, e.g. in the Black Forest, summer precipitation decreased even by more than

100 mm. Autumn precipitation increased mainly in the southern parts (regions AL, ALV, OMG, SMG) by up to 140 mm (30-50%) in the mountain ranges.

Patterns that can be found in seasonal precipitation totals are quite differently pronounced in the associated months. Although January, February and December show only rather few stations with significant trends that are not field significant for any region, winter precipitation trends are much more distinctive. The same conclusion, i.e. single months do not necessarily show the same spatial pattern of trends as the season to which they belong, can be drawn for almost all months. Seasonal results rather seem to be a composition of the 3 contributing months: trend patterns that are well pronounced in a single month or are similar in different months are expressed in the seasonal result as well (e.g. compare the superposition of positive trends for March, April and May, leading to pronounced positive trends in spring for the Southwest of Germany, east of the Rhine). Contradicting trend directions in 2 months cancel out each other, leading to insignificant change in the respective season (e.g. compare March and May with spring for the very South of Germany). This result should serve as a note of caution for previous studies (as in Section 1 and Table 1): trend results obtained on a seasonal basis might not be valid for single months.

Several months showed interesting spatial patterns of significant trends. March revealed significantly increasing precipitation in 5 out of 7 regions and for 24% of all stations, whereas April and May showed only weak changes (except May where a decrease of precipitation in the Alps was found). Thus the change in spring precipitation was mainly influenced by changing March precipitation. June showed significantly decreasing precipitation of up to 60 mm for 24% of all stations and for all regions except the Alps and the Northwest German Plain. July precipitation revealed only very few and weak trends, and the change of August precipitation is rather located in the west. The increase in autumn precipitation in the southern half of Germany arose from quite distinct patterns in the respective months: in October strong spatial clustering of positive trends was found in the Black Forest (southwest) and surroundings whereas the increase in November precipitation was manifested mainly in the southeast and central-east.

It can be summarized that strikingly clear spatial patterns of trends in seasonal and monthly precipitation totals emerged. Stations showing significant trends are not erratically located but tend to be strongly spatially clustered. Increasing and decreasing trends are never found in direct neighbourhood, but are well separated from each other. It is also worthwhile to notice that the trend patterns of succeeding months are quite distinct from each other and that seasonal trend patterns are hardly found in the respective months. Therefore, trend studies should not be limited to seasonal analyses only, but should also check single month (if an appropriate data base is available).

4.2 Changes in mean, variability and heavy precipitation indicators

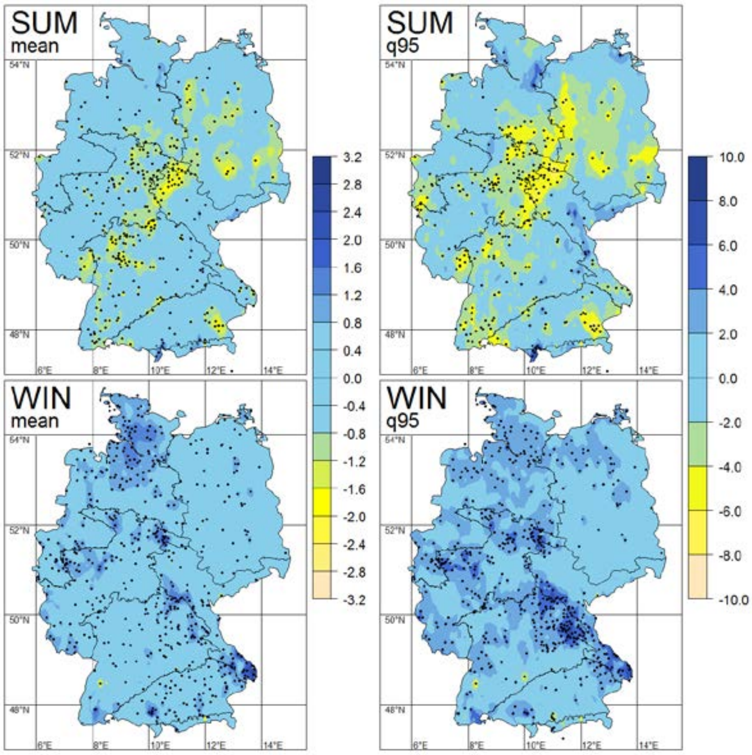

Figure 4. Change of mean and upper quantile of the Gamma distribution of daily precipitation for summer and winter (in mm for 1952-2006). Plot as in figure 2.

Figure 4 shows the trend results for the mean and the 95%-quantile of the daily precipitation amounts for winter and summer. A remarkable attribute of these results is that, for a given season, the spatial patterns are very similar. This means the standard deviation (not shown here) increases (or decreases) in accordance with the mean, and hence, the upper quantile increases (or decreases) with a similar pattern. To better understand the patterns of change in mean precipitation we analysed various empirical quantiles of the data as well (not shown here). We found that in winter increasing mean precipitation in the North is caused by changes over the complete distribution whereas in the Southeast only upper quantiles increase resulting only in small changes of the mean. In summer the patterns of trends are solely influenced by the upper quantiles, lower quantiles do not show any spatial pattern but are very heterogenous. Another striking characteristic is the direction of trends (figure 4 and table 2). Whereas almost all significant trends in winter are positive, the great majority of trends in summer is negative. In winter, stations showing significant trends are focussed in the north, west and southeast with regions NOT, NWT, WMG, and OMG being field significant for both indicators. In contrast to that, summer exhibits a pattern of negative trends that is field significant for all indicators in the West Central Uplands, and significant only for the mean in the Northeast German Plain, Southwest Uplands and East Central Uplands.

The results for spring and autumn are not shown here. However, it can be summarized that an increase of up to 7 mm (for 1952-2006) in spring and 13 mm in autumn for the 95%-quantile was found with significant changes in regions NWT, SMG, WMG, and ALV for spring, and NWT, SMG, and WMG for autumn.

4.3 Transition probabilities

4.3.1 Spatial pattern

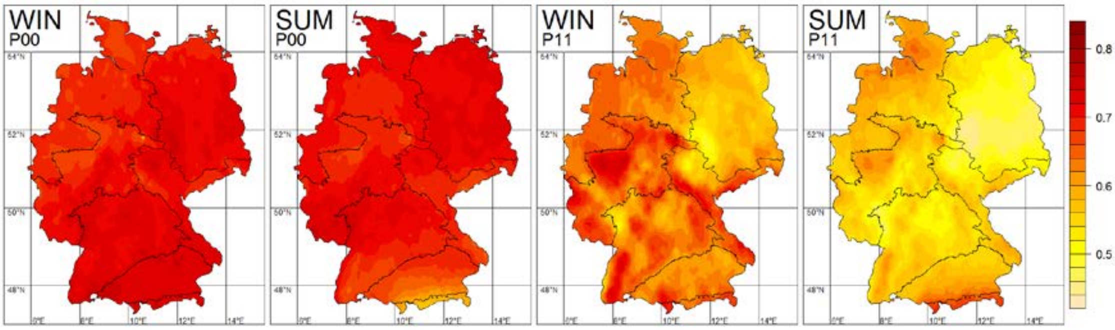

Figure 5. Transition probabilities P_{00} and P_{11} (as fraction) for summer and winter, mean value for 1951-2006.

Figure 5 shows the spatial pattern, averaged over 1951-2006, of transition probabilities P_{00} and P_{11} for winter and summer. Transition probability P_{00} is always greater than 0.5, which means there is a higher probability that a dry day follows after another dry day compared to a change from dry to wet. In contrast, transition probability P_{11} could fall below 0.5 in some regions and seasons. The probability for transition P_{00} is quite high in winter (approx. 0.66-0.76). However, it has to be taken into account that the transition probabilities are influenced by the chosen threshold (0.5 mm) for assigning a day as wet or dry. Further, P_{00} is rather homogeneously distributed over Germany with slightly lower probabilities in the northwest of Germany and some low mountain ranges of east-central Germany. In contrast to that, P_{11} shows a marked spatial pattern which has large similarities to the spatial pattern of total precipitation (not shown here) – mountainous parts of the west and south (except the Alps) have highest transition probability P_{11} with values around 0.66-0.84. Lowest probabilities were found on the lee side of the Harz Mountains in central-east Germany. This result can be explained by the fact that lee sides and the east get relatively low precipitation in winter, and thus, the probability for two wet days in a row is quite small. In summer, the spatial pattern of P_{11} has some similarities to winter, however, the values are lower. In contrast, the values of P_{00} are somewhat higher in summer compared to winter for most parts in the north and west, whereas the south and south eastern mountain ranges show lower values of P_{00} with probabilities as low as 0.56 in the Alps, exhibiting a similar pattern as total summer precipitation (not shown here). The patterns of spring and autumn transition probabilities (not shown) are similar to those of summer and winter with intermediate values.

4.3.2 Trends in transition probabilities

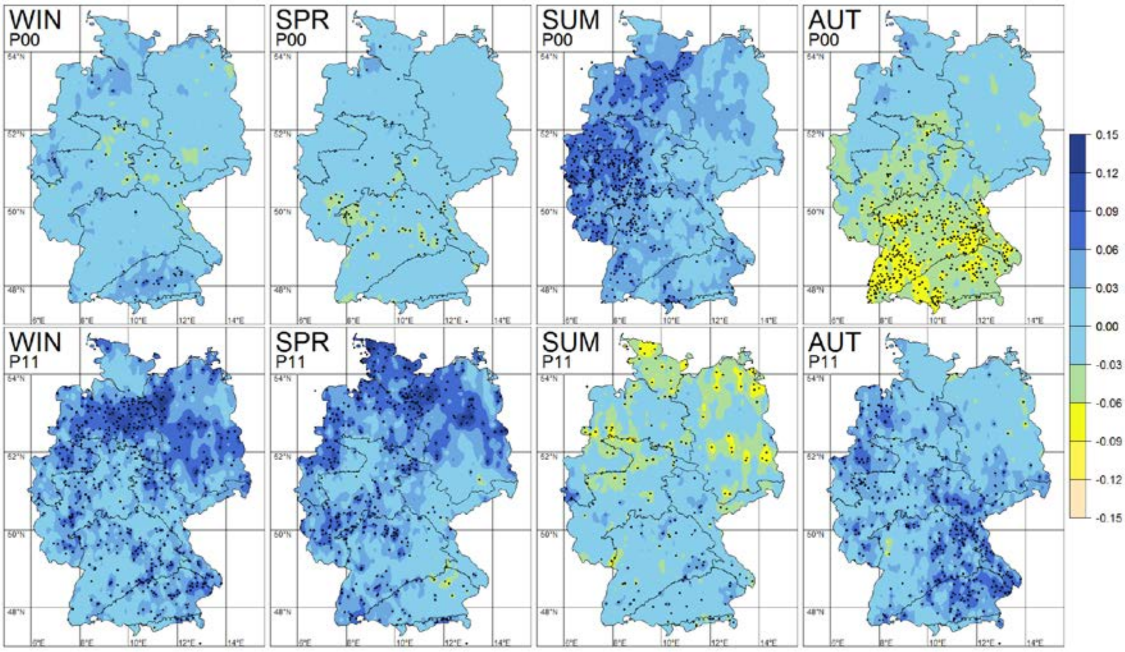

Figure 6. Change of transition probabilities P00 and P11 (as fraction for 1952-2006) for all seasons. Plot as in figure 2.

The trend results for transition probabilities are given in figure 6. P_{00} (dry-dry) shows no particular trends in winter and spring, but an increase in the west in summer and a decrease in the south in autumn, which denotes a tendency for longer dry spells during summer in the west and shorter dry periods in autumn in the south of Germany. This supports the observed trends in seasonal total precipitation. As summer tended to become drier, longer dry periods might occur and P_{00} increased. For autumn, decreasing P_{00} means that dry periods were more often interrupted by rainfall which resulted in higher total precipitation, mainly in the south for which a trend towards higher precipitation was observed. The absolute change of P_{00} is in the range of +0.03-0.09 in summer and -0.03- -0.09 in autumn. For transition P_{11} (wet-wet), an upward trend of the probability in the range of +5-15% was observed in winter in all regions of Germany except the Alps. Thus wet spells tend to last longer which is in line with observed increasing winter precipitation. In the west and north and in the Alps, P_{11} increased also in spring (+5-15%); in the south and west, P_{11} increased in autumn (+5 – 10%).

4.4 7-day precipitation amount with return period 100 years

4.4.1 Spatial pattern, average over 1952 – 2006

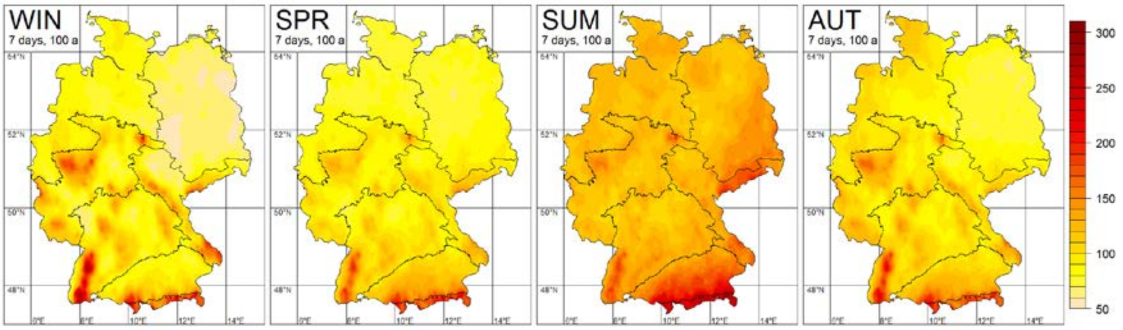

Figure 7. 7-day precipitation amount with return period 100 years (in mm) for all seasons, mean value for 1952-2006.

Figure 7 shows the 7-day amount of precipitation with a return period of 100 years for each season. The patterns of each season are again very similar to those of total precipitation (not shown here). Salient features of these patterns are the strong control by orography, low values in the east for winter, rather homogeneous values all over Germany and highest values in the Alps for summer, and intermediate values for spring and autumn. These patterns should not be surprising as the parameters that entered our Monte Carlo procedure (pdf (annually averaged results not shown here) and transition probabilities) follow similar patterns. Far more interesting are the huge differences of multi-day precipitation amounts. For instance, an event that has a return period of 100 years in the east of Germany might occur at least once a year in the Alps. For winter the precipitation depth of the 100-year/7-day event varies from 50-70 mm in the eastern lowlands, 70-100 mm in the western and southern lowlands and up to 260 mm in the mountains. In summer the range extends from 90-160 mm for most regions of Germany to 310 mm in the Alps.

4.4.2 Trends in extreme, multi-day precipitation

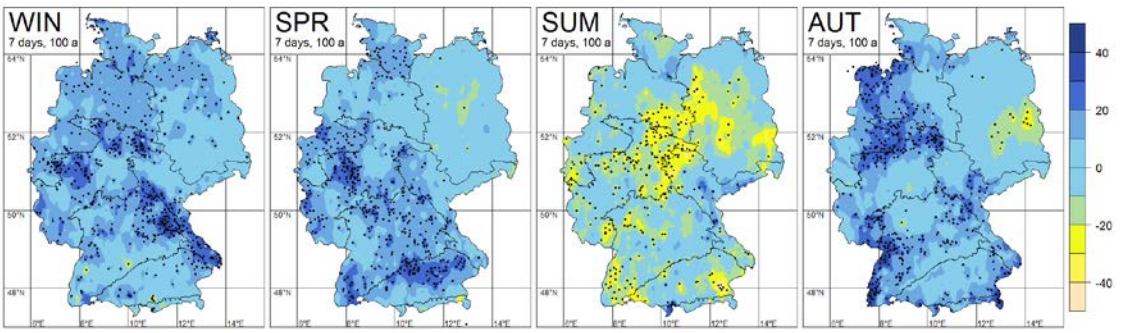

Figure 8. Change of 7-day precipitation amount with return period 100 years (in mm for 1952-2006) for all seasons. Plot as in figure 2.

In figure 8 the change of the precipitation amount of the 100-year/7-day event during 1952-2006 is shown. In winter we detected an increase by around +10-40% in all regions except the Alps and the Alpine Foreland with the highest increase in the East Central Uplands (up to +60%). In spring there is an increase of up to 40% in the west (regions NWT, SMG, WMG) and the Alpine Foreland. For summer a field significant downward trend of up to -30 mm was found in the West Central Uplands. Autumn showed increasing extreme precipitation in the west.

Interestingly, the spatial patterns of all seasons are very similar to the results of the trend analyses for the parameters of the Gamma distribution, whereas the patterns of the changes in transition probabilities cannot be identified. This shows that the observed changes in the pdf dominate the changes in the 100-year/7-day precipitation event. The changes in transition probabilities are mostly below 15%, and are comparatively small.

5 Conclusions

This paper used a quality-controlled data set of a very dense network of 2342 precipitation stations with an average distance of 12 km between stations for the period 1951-2006 for Germany. The data base allowed a comprehensive analyses of spatio-temporal precipitation patterns. The time series of daily precipitation values for each station were used to derive an indicator set describing different characteristics of precipitation: (1) precipitation totals to capture the changes at the monthly and seasonal time scale, (2) mean and 95%-quantile to represent the daily precipitation behaviour, (3) transition probabilities to describe persistence of daily precipitation, and (4) 7-day precipitation amount with return period 100 years to exemplify the combined effect of changes in persistence and in the probability density function of daily precipitation on multi-day, heavy precipitation.

For all indicators strikingly clear spatial trend patterns emerged. Stations showing significant trends are not erratically located but tend to be strongly spatially clustered. Increasing and decreasing trends are never found in direct neighbourhood, but are well separated from each other. These clear spatial patterns are an expression of the spatial organisation of precipitation mechanisms over Germany.

The trends in monthly and seasonal precipitation totals show not only clear spatial patterns, but also very distinct seasonality. The trends can be roughly summarised as getting wetter in winter, spring and autumn, and getting drier in summer. However, it has to be noted that these trends are composed of different spatial patterns, for instance, the increase in winter is particularly pronounced in the south-east and north-west, whereas the spring increase is especially distinct in the west. Interestingly, the further stratification of seasonal totals in monthly totals yielded different trend patterns, i.e. trend patterns of succeeding months are quite distinct from each other, and the trend patterns of individual months can significantly depart from their seasonal value. Hence, trend analyses at the seasonal scale may not disclose the complete range of changes.

The overall patterns of trends detected at the seasonal time scale can also be seen at the daily scale: Whereas almost all significant trends of daily precipitation indicators are positive in winter, the great majority of trends in summer is negative, and moreover, the clusters of increasing or decreasing stations are similar in both cases.

Our analyses show increasing heavy precipitation for winter, spring and autumn, but show the opposite trend for summer precipitation.

In order to complete the description of changes in daily precipitation, we analysed the spatio-temporal behaviour of transition probabilities. P00, the probability of two dry days in sequence, is rather homogeneously distributed over Germany. In contrast, P11, the probability of two wet days in sequence, shows a clear spatial heterogeneity with highest probabilities in the mountainous parts of the west and south (except the Alps) and the lowest values in lee zones (especially east of the Harz Mountains). There is also a clear seasonal effect: lower P11 values and higher P00 values in summer, respectively, compared to winter transition probabilities. Trends of transition probabilities show an overall increasing persistence for wet spells in winter, spring and autumn. However, this increase is region-specific. For example, the increase in spring is particularly marked in parts of north and north-east Germany, and there are regions, e.g. Saxony and Bavaria, which do not show any change. Increased persistence (higher P00 and higher P11, see Fig 6) is found especially in the Northwest German Plain (except summer), but also for many regions in winter and spring; in contrast to that, autumn shows strong signals towards longer wet spells and shorter dry spells in all regions except the NWP. The contrary behaviour is found for summer in the northern half of Germany: longer dry spells and shorter wet spells.

The overall result of increasing persistence is in accordance with results of Petrow et al. (2009) who analysed flood trends and their potential climatic causes across Germany for the same period. They found a tendency for increasing persistence of rainfall-causing atmospheric circulation patterns, especially for the winter half-year (November-April). Changes in the persistence of dry spells are less distinct. However, there is a clear tendency for longer dry spells during summer in the west and shorter dry periods in autumn in the south of Germany. This increase in persistence might be linked to global warming, since reduced meridional temperature gradients tend to lower the steering velocity of weather patterns and seem to favour amplified waves with increased meridional wind components (e.g. Francis et al., 2012).

The combined effect of daily precipitation amount and persistence on multi-day heavy precipitation was exemplarily analysed for the 100-year/7-day event. The spatial pattern, averaged over the complete period, shows huge differences, from 50-70 mm in the eastern lowlands up to more than 300 mm in the Alps. The differences within a season and between seasons can be explained by different precipitation formation processes: areal frontal precipitation plus localized, but stationary orographic upslope enhancement in winter; much more localized convective precipitation in summer, being pronounced in certain regions (low mountain ranges and Alpine Foreland due to Alpine pumping). The footprint of the cyclone track Vb (van Bebber, 1892) is clearly visible in summer in Saxony, Brandenburg and in the south and east of Bavaria.

The results of the trend analyses show that, overall, the 100-year/7-day precipitation amount increased during winter, spring and autumn. Strong increase is confined to parts of Germany, differently for different seasons. For some regions the increase is remarkable, e.g. an increase in the order of up to 50 mm in the south-east and central-west in winter. The overall tendency for summer is downward with the highest decrease of up to -30 mm in central Germany.

Multi-day, heavy precipitation is closely connected to the occurrence of regional flooding, especially on time-scales of a few days. Recent experience, e.g. the May/June 2013 flood in the Elbe and Danube catchments in Central Europe, underlines that multi-day rainfall accumulations may lead to disastrous flooding. Such extreme precipitation events are becoming more likely with increased persistence. However, the cyclone track across the catchment areas and the timing play an important role, too.

In summary, remarkable changes in daily precipitation are observed during the second half of the 20th century. Based on a very high density of stations, it is shown that temporal changes are spatially well structured. In case the observed trends continue, there will be an increasing potential for floods in winter and spring, e.g. in parts of north-west and south-east Germany, and at the same time, increasing probabilities for water stress in summer in regions that show signs of water stress today.

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Tables

Table 1. Overview on available studies on precipitation changes and extremes for Germany, Europe and the World. The analyses methods used are summed up and for some studies results are also summarised.

Author	Region	Period	No of stations	Precipitation behaviour analysed	Indicators used	Results
Brienen et al. (2013)	west and south Germany	1901-2000	118	Empirical distribution, grouping stations to regions via PCA, assessing stability of trends	• Total precip per season • Wet day frequency • Max no consecutive dry days • Mean wet day intensity • 90th percentile • Precip amount from days exceeding 90th percentile • Max precip during 5 consecutive days • Max daily precip	• Increase in intensity-related indices in summer in W-GER • Max no of consecutive dry days increased in Foothills of the Alps and very south of Germany • In first half no signif. trend in winter, in summer increasing trend in intensity-related indices in central W-GER, increase in max no of consecutive dry days in the south • In second half decrease in summer precip and frequency of wet days, increase in max no of consecutive dry days, for winter increase in intensity-related indices

Author	Region	Period	No of stations	Precipitation behaviour analysed	Indicators used	Results
Haensel et al. (2009)	central-east Germany	1851-2006 1951-2006	2 ~200	Monthly rainfall	• Trends of annual, summer, winter and monthly precip	• Increase in winter precip and decrease in summer half year • Decrease in agricultural used lowlands and during first vegetation period • Decrease in extreme precip and frequency in summer • Increase of frequency in high precip classes for winter • Mar, Nov – high precip increase; Apr, May, Oct – decrease
Hundecha & Bardossy (2005)	German parts of Rhine basin	1958-2001	611	Daily extremes (annual and seasonal basis)	• 90^{th} percentile of daily precip • Max 5-d-total precip • Daily intensity • Max no of consecutive dry days • Fraction of precip amount from daily events > long-term 90^{th} percentile • No of days with precip > long-term 90^{th} percentile	• Increase in heavy precip in spring • Decrease in extreme precip and frequency in summer • Increases extreme precip in autumn
Lupikasza et al. (2011)	central eastern Germany (and southern Poland)	1951-2006	19 (GER)	Daily extremes (seasonal basis)	• Max 1-day precip • Max 5-day total precip • Precip total for days > 90^{th} percentile, > 95^{th} percentile • No of days with precip > 90^{th} percentile, > 95^{th} percentile • Precip intensity for days with precip > 90^{th} percentile, > 95^{th} percentile	• Winter: clear increases in amount, frequency, intensity • Spring & autumn: overall increase, but less prominent • Summer: increase dominates, but also significant decreases

Author	Region	Period	No of stations	Precipitation behaviour analysed	Indicators used	Results
Troemel & Schoenwiese (2007)	Germany	1901-2000	132	Monthly extremes	• 5^{th}, 95^{th} percentiles of monthly precip	• Decrease in extreme precip and frequency in summer • Decreasing probability of precip > 95^{th} percentile in autumn, NE-GER
Zolina et al. (2008)	western and southern parts of Germany	1950-2004	2125	Daily extremes, (annual and seasonal basis)	• 95^{th}, 99^{th} percentiles of daily precipitation • Precipitation total • No of wet days • Precip intensity	• Heavy (90^{th}) and extreme (95^{th}) precip increased ~5-13% per decade in winter, spring, autumn • Heavy (90^{th}) and extreme (95^{th}) precip decreased ~3-9% per decade in summer • Winter: large precip increasing; weak precip decreasing • Summer: decreases for all classes
Zolina (2014)	Germany	1950-2008	3161	Wet spells (WP) in warm and cold season	• Length of spells • Trend of mean and extremely long WPs	• average duration of wet spells highest in mountains and coastal areas • Significant changes only in cold season (increasing intensities in long WPs, decreasing in short WPs)
Besselaar et al. (2013)	Europe	1951-2010	478	Changes in seasonal extreme precip	• Max 1- and 5-day prec of each 20y period of the time series (with 10y overlap) • Return period for these extremes	• Increasing extremes in winter and spring in N-Europe • Summer extremes nearly constant in N-Europe

Author	Region	Period	No of stations	Precipitation behaviour analysed	Indicators used	Results
Klein Tank & Koennen (2003)	Europe	1946-1999		Daily extremes (annual basis)	• Max 1-day precip • Max 5-day precip • No of days with precip > 10 mm, > 20 mm • No of days with precip amount > 75th percentile, > 95th • Precip fraction due to very wet days (> 95th)	• wet extremes increase • disproportionate large change in extremes where annual amount also increases
Moberg et al. (2006)	Europe	1901-2000	223	Seasonal totals and daily precip	• Precip total • Simple daily precip intensity • 90th, 95th, 98th percentile of daily precip	• Increase in winter precip totals • Increase in upper percentiles in winter • No significant overall trend in summer
Pauling & Paeth (2007)	Europe	1700-2000 (reconstruct ted)	0.5° grid	Changes of return periods of seasonal winter precip extremes	• Fitted Gamma to seasonal sums	• Winter precipitation: more extreme • Dry winters: more often over central Europe during past 300 years • Many other parts of Europe: extremes less frequently during last 300 years compared to 1951–2000

Author	Region	Period	No of stations	Precipitation behaviour analysed	Indicators used	Results
Zolina et al. (2005)	Europe	1804-2003	295, 96	Heavy precip	• Seasonal totals • Number of seasonal wet days • Seasonal mean precip intensity • Occurrence of exceedance of given threshold, e.g. 95^{th} or 99^{th} • Percentage of seasonal total precip sum obtained during very wet (> 95^{th}) days • 95^{th}, 99^{th} percentiles of Gamma distribution for daily precip	• Increasing frequency and intensity of heavy precip over most Europe • For summer decrease in northern Europe and increase in southern Europe
Zolina et al. (2009)	Europe	1951-2000	116	Heavy and extreme precip, daily data	• fractional contribution of very wet days to precipitation total	• increase in winter, decrease in summer extremes
Zolina et al. (2010)	Europe	1950-2008	699	Wet spells and dry spells	• Duration and intensity	• Longer wet periods over most of Europe, no increase of total number of wet days
Zolina et al. (2013)	Europe	1950-2009	699	Wet spells and dry spells	• Duration	• Duration of wet spells increases over northern Europe and central European Russia, especially pronounced in winter • Summer wet spells shorter over Scandinavia and northern Russia • Duration of dry spells decreases over Scandinavia and southern Europe in winter and summer

Table 2. Trend results for all precipitation characteristics analysed: Monthly and seasonal total precipitation; seasonal mean, 95%-quantile (q95); seasonal transition probabilities and seasonal multi-day-precipitation. Number and percentage of stations with significant upward or downward trend, respectively. Plus signs (minus signs) indicate field significance in upward (downward) trends for the region as described in section 3.2. Significance level: 10%.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	WIN	SPR	SUM	AUT
								total precipitation								
up	6 (0%)	123 (5%)	559 (24%)	27 (1%)	31 (1%)	23 (1%)	25 (1%)	9 (0%)	76 (3%)	304 (13%)	429 (18%)	50 (2%)	249 (11%)	430 (18%)	2 (0%)	348 (15%)
down	25 (1%)	2 (0%)	0 (0%)	33 (1%)	29 (1%)	562 (24%)	42 (2%)	383 (16%)	0 (0%)	0 (0%)	1 (0%)	0 (0%)	6 (0%)	1 (0%)	445 (19%)	1 (0%)
AL			+		-				+		+					+
ALV			+			-					+				-	+
NOT						-									-	
NWT			+					-					+	+		
OMG			+			-					+		+			+
SMG						-		-		+	+			+	-	+
WMG			+			-		-						+	-	

Table 2 (continued)

	WIN		SUM		WIN	SPR	SUM	AUT	WIN	SPR	SUM	AUT	WIN	SPR	SUM	AUT
	mean	q95	mean	q95	P_{00}				P_{11}				7d/100a precipitation			
up	513 (22%)	522 (22%)	38 (2%)	39 (2%)	38 (2%)	10 (0%)	487 (21%)	7 (0%)	520 (22%)	415 (18%)	54 (2%)	360 (15%)	513 (22%)	438 (19%)	25 (1%)	472 (20%)
down	26 (1%)	11 (0%)	314 (13%)	257 (11%)	22 (1%)	78 (3%)	1 (0%)	440 (19%)	8 (0%)	14 (1%)	120 (5%)	14 (1%)	11 (0%)	9 (0%)	261 (11%)	19 (1%)
AL								-		+						+
ALV	+							-	+			+		+		
NOT	+	+	-						+	+			+			
NWT	+	+					+		+	+		+	+	+		+
OMG	+	+	-					-	+			+	+			
SMG		+	-				+	-	+				+	+		+
WMG	+	+	-	-			+		+	+			+	+	-	+