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Seasonally dependent changes of precipitation extremes over Germany since 1950 from a very dense observational network

Olga Zolina,[1,2] Clemens Simmer,[1] Alice Kapala,[1] Susanne Bachner,[1]
Sergey Gulev,[2] and Hermann Maechel[3]

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[1] The newly updated collection of daily precipitation measurements over Western Germany (more than 2000 stations in total) is used to analyze linear trends in extreme and heavy precipitation for different seasons over the period 1950–2004. Heavy and extreme precipitation has been quantified using the 95% and 99% percentiles with respect to the Gamma distribution fitted to daily precipitation data. The significance of linear trends was quantified using several statistical tests including estimates of field significance. Positive linear tendencies in heavy precipitation for the winter, spring and autumn seasons were found for the whole domain with the largest increase of 13% per decade in Central and Southern Germany. For the summer season, however, heavy precipitation exhibits mostly negative trends of up to 8% per decade e.g., for the Central and Southwestern parts of Germany. Trends derived from the estimates of heavy precipitation without seasonal breakdown, however, do not show any clear spatial pattern. Estimates of field significance show that the conclusions concerning the seasonal diversity in trend sign hold for most of Western Germany. The results are insensitive to changes of the beginning and the end of the records by several years; thus the seasonal linear trend patterns are not influenced by interdecadal variability. Seasonality is also identified in the linear trends of mean precipitation characteristics. Analysis performed for different classes of precipitation intensity shows that during winter the linear increase of heavy and extreme precipitation is associated with downward linear tendencies for weak precipitation. In summer statistically significant negative linear trends were identified for all classes of precipitation intensities. Our results also imply that the amplitude of the annual cycle of heavy and extreme precipitation underwent a considerable decrease during the last 55 years between 30% to 60% per decade.

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1. Introduction

[2] Most analyses of observed precipitation hint at an increasing probability of extreme precipitation over Europe during the last several decades and the last century [*Easterling et al.*, 2000; *Frei and Schär*, 2001; *Groisman et al.*, 2005; *Klein Tank and Koennen*, 2003; *Zolina et al.*, 2005; *Brunetti et al.*, 2006; *Alexander et al.*, 2006]. A similar conclusion is drawn from analyses over the North American continent [*Kunkel et al.*, 1999, 2003]. The IPCC Fourth Assessment Report (AR4) [*Trenberth et al.*, 2007] confirmed an increasing number of heavy precipitation events over the last 50 years. Less evidence is available concerning a seasonal differentiation although seasonality in trends of mean European precipitation and temperature [*Shabalova and Weber*, 1999; *Datsenko et al.*, 2001; *Zveryaev*, 2004] suggests seasonality of trends for extremes too. Since the circulation patterns, which provide moisture to Europe, differ between cold and warm seasons, their long term changes are not necessarily correlated. Also the respective roles of large-scale processes and local mechanisms in leading to extreme precipitation are quite different during the cold and the warm seasons. Finally, extreme precipitation is constrained by the atmospheric moisture content while mean precipitation is constrained by the energy budget of the troposphere [*Allen and Ingram*, 2002], leading to an additional reason to expect seasonal dependence in characteristics of extreme precipitation. Recently *Moberg et al.* [2006] analyzed winter and summer trends in mean and extreme precipitation indices over Europe during 1901–2000. They found significant increases in winter heavy and extreme precipitation, while linear trends in summer were

[1]Meteorologisches Institut, Universitaet Bonn, Germany.
[2]P.P. Shirshov Institute of Oceanology, Moscow, Russia.
[3]Deutscher Wetterdienst, Offenbach a.M., Germany.

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found to be mostly insignificant and regionally dependent. Seasonal trends in extreme precipitation were also analyzed for both the ERA-40 and NCEP/NCAR reanalyses, although the differences hardly exceed any reasonable level of statistical significance [*Zolina et al.*, 2004].

[3] Understanding and quantifying seasonality of linear trends in precipitation extremes provides an additional metric for the validation of climate model experiments which aim at attributing observed and predicting future climate change because seasonality would lead to changes of the amplitude of the annual cycle along with those of mean annual characteristics. Most climate model experiments show an increasing occurrence of extreme precipitation under anthropogenic warming conditions [*Zwiers and Kharin*, 1998; *Semenov and Bengtsson*, 2002; *Palmer and Raelsaenen*, 2002; *Watterson and Dix*, 2003]. *Kiktev et al.* [2003] showed indications of growing intensity of precipitations extremes in present climate simulations. *Tebaldi et al.* [2006] analyzed historical and future simulations concerning the characteristics of extreme precipitation from an ensemble of 9 GCMs contributing to the AR4. They reported that eight of the nine analyzed GCMs show a tendency toward a larger frequency of heavy precipitation events over the past four decades at high latitudes of the Northern Hemisphere and particularly in Central Europe, which are broadly consistent with observed changes [*Groisman et al.*, 2005; *Hegerl et al.*, 2007]. Analyzing predicted trends for individual seasons from a greenhouse gas experiment with the ECHAM4/OPYC3 model *Semenov and Bengtsson* [2002] reported opposite signs of linear trends in mean precipitation for winter and summer over Europe. Similar results are reported by *Watterson and Dix* [2003] based on the CSIRO Mark 2 model simulations. Recently *Li et al.* [2006] showed that the climate model spread in regional climate change projections for the Amazon region can be associated with the strong seasonality of rainfall in this area.

[4] Seasonality in precipitation variability may also result in seasonal signals in extreme flooding, as it has been shown using observed data and modeling results for Canada [*Leung and Qian*, 2003; *Remillard et al.*, 2004]. Understanding and quantifying seasonality in changes of precipitation extremes improves the assessment of hazardous flood risks, which is still poorly developed compared to e.g., seasonality effects in coastal surges [*Coles and Tawn*, 2005].

[5] Regional studies focused on past century records [*Frei and Schär*, 2001; *Brunetti et al.*, 2004, 2006; *Zolina et al.*, 2005] so far did not hint at a clear seasonality in extreme precipitation trends over the European continent as a whole. *Frei and Schär* [2001] analyzed centennial records of the Alpine region and revealed primarily increasing heavy and extreme precipitation of different categories for all seasons. *Brunetti et al.* [2004] indicate that at least in Central and Northwestern Italy linear trends in the occurrence of heavy precipitation are different between the cold and warm season, but the statistical significance of the findings seems questionable. Indications of opposite tendencies in extreme precipitation for different seasons were also found by *Brunetti et al.* [2006] using long Italian rain gauge records. Significant seasonal changes in the tendencies of extreme precipitation were also found for the United Kingdom by *Fowler and Kilsby* [2003]. The analysis of regional changes in mean precipitation over Belgium during the last 105 years [*De Jongh et al.*, 2006] has shown a clear increase of the amount of rainfall between December and March and a less evident signal for the other seasons. *Zolina et al.* [2005] analyzed extreme precipitation variability in centennial European daily records using the ECA (European Climate Assessment) collection [*Klein Tank et al.*, 2002]. They did find seasonally different trend signs and magnitudes in Central Western Europe, but no changes of signs or magnitudes of linear trends in Eastern Europe.

[6] Since seasonality in long-term changes of precipitation extremes may be strongly localized, the large and usually less homogenized data sets with high spatial resolution should be compared to high quality but coarse resolution data collections such as ECA [*Klein Tank et al.*, 2002]. Recently *Hundecha and Bardossy* [2005] using a subset of high resolution station data in the Rhine river basin reported different signs of trends for winter and summer extreme precipitation indices for the period 1958-2001. For the 90% percentile of daily precipitation, they reported an overall 20% winter increase and a more than 6% summer decrease with an annual increase of about 4%.

[7] In this study we analyze an updated station collection with very high spatial resolution over Germany in order to characterize extreme precipitation trends for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) over the past 55 years from 1950 to 2004. First we describe data and pre-processing procedures (section 2). In section 3 we briefly present the used methods to estimate linear trends and their statistical significance. Section 4 will show linear trend estimates for extreme precipitation for different seasons including significance tests. In section 5 we compare the observed seasonality in linear trends of precipitation extremes with trends in the mean precipitation characteristics, and we also analyze linear tendencies for different classes of precipitation intensities. Finally, conclusive section 6 will discuss the results in the light of their reliability and potential implications for the European climate.

2. Data and Pre-Processing

[8] Our study is based on the updated collection of daily data from the operational rain gauge network of the German Weather Service (DWD) covering Germany with a very high spatial resolution (5454 stations) (Figure 1a). This outstanding data collection is currently updated and considerably extended including the digitization of new data from hand-written reports. Of these 5454 stations only 2125 have been selected for the analysis. In a first step only those stations which cover the period from January 1950 to June 2004 (2701 locations) were selected (Figure 1a). These stations were then checked for gaps in the records based on sampling requirements put forward by *Zolina et al.* [2005] who analyzed the effect of missing values onto trend estimates in extreme precipitation. They have shown that above 30%–40% of missing values trend estimates in extreme precipitation are severely affected, and that for less than 10% of missing values effects are practically negligible. Although most of the stations covering the period 1950–2004 meet the sampling requirements of *Zolina et al.* [2005] (Figure 1b), we selected for this study an even lower threshold of 5% of missing values which reduced the

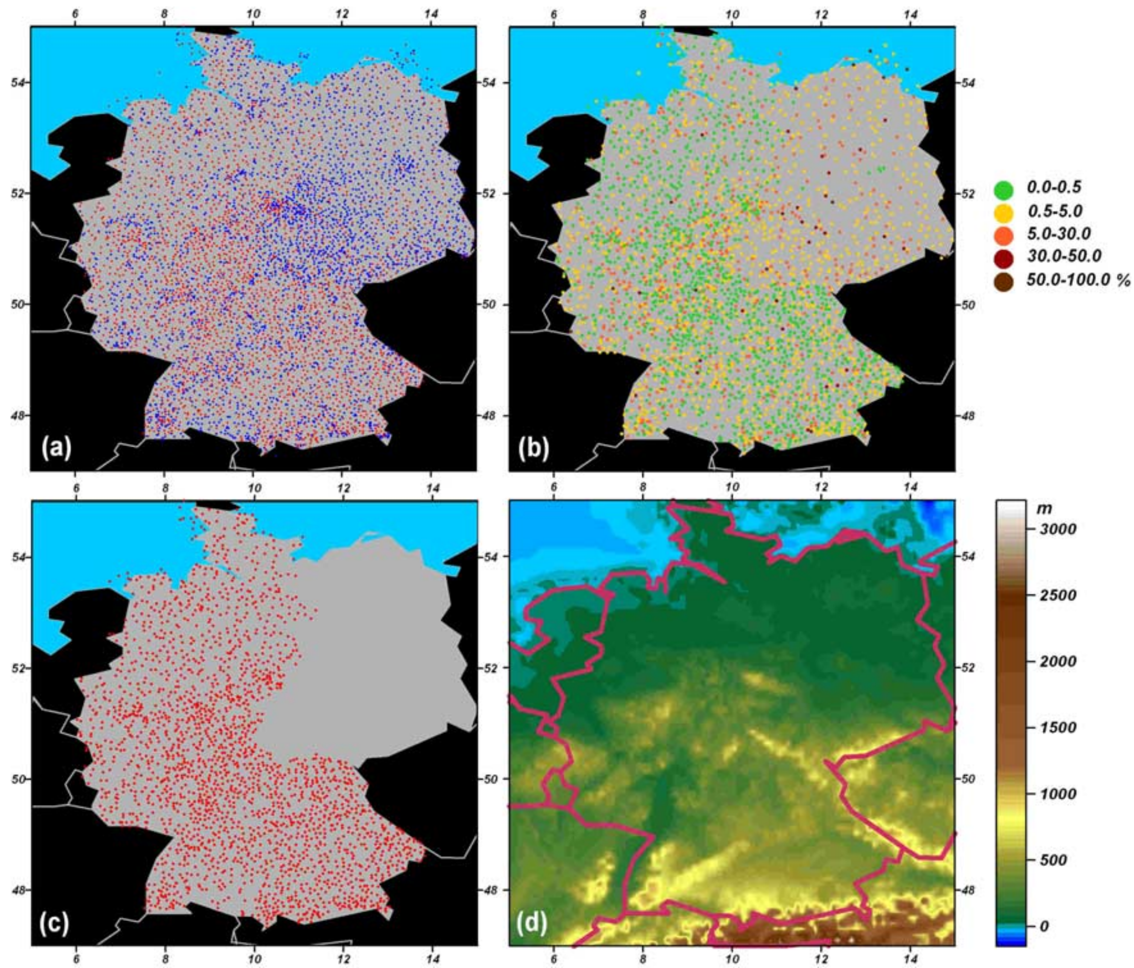

Figure 1. (a) Operational rain gauge network of the German Weather Service. Red points show the rain gauges covering the period 1950–2004 and blue points show the rain gauges which do not cover 1950–2004 period. (b) Percentage of missing values (%) in the daily precipitation data for the rain gauges covering the period 1950–2004. (c) 2125 rain gauges meeting sampling requirements and chosen for the analysis. (d) regional orography.

station number to 2701. From this subset we further excluded 576 stations (primarily in the former German Democratic Republic) which lack information about applied observational techniques. Figure 2 shows that the finally selected 2125 stations (Figure 1c) have considerably less gaps compared to the complete data set for the period 1950–2004. Although there is an increase of the percentage of missing values during the last decade, the number of gaps is nevertheless smaller than 5% and, thus, passes the threshold established. In contrast to the complete data set, the selected stations do not show a considerable drop of the number of gaps in 1969. The typical station-to-station distance is 3–10 km in the Southern and Central parts and up to 5–20 km in the Northern and Eastern parts. The accuracy of the reported daily precipitation amounts is 0.1 mm. More than 1300 stations (61%) are located at relatively flat regions with elevations from 0 to 400 meters. About 36% of stations are located at elevations from 400 to 800 meters and 3% of stations are found in the mountain regions with elevations higher than 800 meters. Further details of the quality control, instrumentation used and data processing are given in the Appendix.

3. Estimation of Extreme Precipitation Characteristics and Their Secular Variability

3.1. Characteristics of Extreme Precipitation

[9] For each season we computed the precipitation totals p, the number of wet days n, and the precipitation intensity, ($p_i = p/n$) from the daily precipitation amounts at each station. To quantify extreme precipitation many authors use indices based on empirical thresholds (in contrast to indices derived from fitted theoretical distributions, see below). For example, *Groisman et al.* [2005] and *Hundecha and Bardossy* [2005] used the occurrence of the exceedance of a given threshold, e.g., 95% or 99%, to characterize extreme precipitation. *Klein Tank and Koennen* [2003], *Alexander et al.* [2006] and *Klein Tank et al.* [2006] used the percentage of the precipitation amount accumulated during wet (>75%) or very wet (>95%) days. An even wider range of precipitation indices along these lines was used by

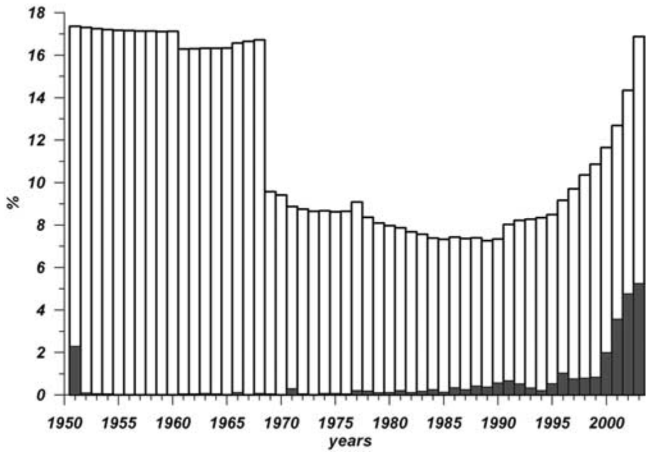

Figure 2. Percentage of the number of missing values in daily precipitation records during the period 1950–2004 at all rain gauges of the operational rain gauge network of the German Weather Service (white bars) and at the rain gauges selected for the analysis (grey bars).

Moberg et al. [2006]. Although objective these approaches have some shortcomings associated with the uncertainty of estimation for small numbers of wet days. This limitation becomes particularly evident when the indices are derived for individual seasons and not for the year-round time series as done by *Groisman et al.* [2005] and *Klein Tank and Koennen* [2003].

[10] We characterized extreme precipitation by the seasonal values of 95% (p_{95}) and 99% (p_{99}) percentiles of daily precipitation for individual seasons or years. These estimates can be formally attributed to heavy (p_{95}) and extreme (p_{99}) precipitation according to *Groisman et al.* [2005]. These parameters were derived, however, from fits of a Gamma distribution to the seasonal or annual records of daily precipitation values [*Wilks*, 1995; *Groisman et al.*, 1999; *Zolina et al.*, 2004]. In the work of *Zolina et al.* [2005], we compared the empirical indices of extreme precipitation [*Klein Tank and Koennen*, 2003; *Groisman et al.*, 2005] with 95% and 99% percentiles based on Gamma distribution fits and found locally significant differences in centennial trends estimated from empirical indices and from the fitted Gamma distribution. Moreover, the Gamma-distribution-based indices were found to be more robust to sampling effects. Estimates of extreme precipitation characteristics based on the Gamma distribution was also adopted for daily data analysis by *Groisman et al.* [1999] and *Brunetti et al.* [2004, 2006], for climate model outputs [e.g., *Hennessy et al.*, 1997; *Semenov and Bengtsson*, 2002; *Watterson and Dix*, 2003] and for reanalysis data [*Zolina et al.*, 2004]. Following *Semenov and Bengtsson* [2002] and *Zolina et al.* [2004] we derived the Gamma probability density functions (PDFs) only for $n_{\min} > 5$, $n_{\min}$ being the number of wet days per season, and used the Kolmogorov-Smirnov (*k-s*) test to estimate the accuracy of the fit. For Western Germany for all seasons the number of wet days is typically higher than 15 (in 99.5% of cases). Application of *k-s* test with the null-hypothesis, that the empirical data of daily precipitation are drawn from the Gamma distribution rejected from the analysis at 95% significance level just few calendar seasons in less than 1% of locations. This is consistent with the results of *Zolina et al.* [2004] who showed that the goodness of fit for the station data is better than for reanalyses. The goodness of fit can, however, drop significantly in Southern Europe, which is characterized by small numbers of wet days.

3.2. Estimation of Linear Trends

[11] We computed linear trends in seasonal and annual precipitation parameters based on the least squares procedure. The trend significance was first estimated using the Student *t*-test, which was also used by *Groisman et al.* [2005] and *Klein Tank and Koennen* [2003]. In addition we used the *Hayashi* [1982] reliability ratio (R) which considers the confidence intervals of the statistical significance of trends. If the ratio $|R| \gg 1$, the true value is close to its estimate, and when $|R| > 1$, the null hypothesis (absence of trend in our case) is rejected showing that the trend is statistically significant. When $|R| < 1$ the confidence intervals can be rather wide even if the Student's *t*-test is formally satisfied for a given percentage point; the reliability of the trend estimate will then be questionable. Similarly, *Klein Tank and Koennen* [2003] employed signal-to-noise statistics [*Buishand et al.*, 1988] for analyzing the significance of their estimates. We also used the non-parametric Mann-Kendall test [*Mann*, 1945; *Kendall*, 1975], which was widely adopted for climate and hydrological time series [see, e.g., *Schertz et al.*, 1991; *Maugeri and Nanni*, 1998; *Turkes*, 1999; *Wang and Swail*, 2001; *Brunetti et al.*, 2004; *De Jongh et al.*, 2006 and others]. For most trend estimates we considered the results to be significant at 95% significance levels if they satisfy simultaneously to the Student *t*-test, the Mann-Kendall test, and the Hayashi reliability ratio. In addition to these traditional significance tests we also used estimates of spectra of interannual time series for different seasons at very low frequencies. These estimates were compared with those derived after the linear trends were removed from the data. Statistically significant differences between the estimates of spectral power can be considered as an indication of the presence of trends in the time series. Furthermore, this analysis can be also applied for detecting non-linear (e.g., parabolic) changes, when the 2nd order polynomial trends are removed.

[12] Analyzing trends for the period of 1950–2004, we also assessed the trend sensitivity to the impact of the beginning and the end parts of the record. For this purpose the trend estimates were computed over shorter time series spanning from 47 to 55-years and representing all possible combinations of starting and ending years within the first and the last 5-year periods of the time series. Thus we analyze the impact of the often larger number of gaps during the first and the last years of the period (Figure 2). Furthermore, such an analysis along with estimates of spectra may allow us to distinguish linear trends from multidecadal variability. The estimation of linear trends for different periods results in variations of the number of locations where trends of either sign are significant. We also estimated the field significance according to *Livezey and Chen* [1983] from the binominal distribution. These estimates show the required number of passes of single tests

(the number of individual locations with significant trends) necessary to satisfy the overall significance at a given level. Estimates of field significance were used for the analysis of centennial trends in extreme precipitation derived from ECA collection [*Zolina et al.*, 2005; *Moberg et al.*, 2006], for comparison of modeled and observed changes in climate extremes [*Kiktev et al.*, 2003] and for the analysis of the spatial structure of bias errors in numerical model output [*Elmore et al.*, 2006]. Recently *Wilks* [2006] suggested to extent the field significance test to a more powerful test of global or field significance by accounting for the actual values of the single tests and considering their minimum, known as the Walker test [*Katz*, 2002]. This was also applied along with the binary field significance test in our study. This test represents the extension of Bonferroni adjustment of individual tests aimed on the analysis of the probability of family wise type I error [see, e.g., *Keppel and Wickens*, 2004]. However, both these approaches should be used in our case with caution because of high correlations between the data records at neighboring locations.

4. Extreme Precipitation Characteristics and Seasonality of Their Linear Trends From 1950 to 2004

4.1. Climatology of Mean and Extreme Precipitation Characteristics

[13] In order to provide a reference for the discussion of variability we first discuss the climatology of mean and heavy precipitation over the Western Germany. The regional orography, which largely influences the spatial distribution of precipitation is presented in Figure 1d. Figures 3a and 3b show the winter and summer distribution of precipitation intensity (p_i). Although spatial distributions are qualitatively comparable precipitation intensity in winter is typically 15–25% smaller than in summer. The largest winter precipitation intensity (>10 mm/day) is observed in the mountain regions of the Southern Germany. Locally high winter precipitation intensities of 6–8 mm/day are also observed in the elevated regions of the Central Western Germany. Over Central and Northern Germany winter precipitation intensity typically varies between 2 and 4 mm/day. The lowest winter precipitation intensity (2–3 mm/day) is observed in the plain regions of the eastern and central parts of Western Germany. During summer, the largest values are found in the southernmost mountain regions (12–15 mm/day) while the smallest precipitation intensities occur in the plane regions of Central and Northern Germany (3–5 mm/day).

[14] During winter the highest occurrence of the wet days (55 to 65%) is observed in Central and Northern Germany and clearly decreases in toward Southern Germany 40–50% (Figure 3c). The number of wet days in summer (Figure 3d) is typically 1.2–1.6 times smaller than in winter. Also the spatial distribution of the number of wet days in summer is somewhat different from that in winter. The highest summer occurrences of about 60 to 70% are observed in the Southern mountain regions. The smallest number of wet days (less than 40%) is typical for the Central Western part between the latitudes of 49°N and 50°N.

[15] The spatial distribution of heavy precipitation estimated from the Gamma distribution fits (Figures 3e and 3f) is quite similar to that of the mean precipitation intensities. The largest winter values of p_{95} are observed in the mountain regions of Southern Germany where they are higher than 35 mm/day. Locally large p_{95} values of 20–25 mm/day are also observed over elevated areas of Central Germany. The smallest p_{95} values of less than 10 mm/day are observed in Central Germany. During summer (Figure 3f) heavy precipitation estimates vary from 15 to 45 mm/day with a similar spatial distribution as during winter. Locally very high values of heavy precipitation in both seasons are observed in the mountain regions of Southern Germany where p_{95} estimates are typically 3–4 times higher than in Central and Northern Germany.

4.2. Linear Trends in Extreme Precipitation and Their Seasonal Changes

[16] Figures 4a and 4b show estimates of linear trends in annual precipitation intensity and in p_{95} obtained from the daily time series over the Western Germany. Similar estimates, based on annual records were analyzed by *Klein Tank and Koennen* [2003] and *Groisman et al.* [2005]. Spatial distributions in Figure 4 are rather noisy with close-by patches opposite trends. In the central part of Western Germany trend estimates are primarily negative for both p_i and p_{95}, ranging from −1% to −5% per decade with the strongest downward trend of −5% per decade for p_{95} and −10% per decade for p_i. Over the northwestern and the southeastern parts of Germany the trends in precipitation intensity and 95%-percentile of daily precipitation are primarily positive with the largest increases of 6–8% per decade over Northern Germany. Obviously extreme precipitation characteristics estimated from the annual time series do not show a clear signal of either sign over the whole domain. This is especially true for Central and Southwestern Germany where stations indicating trends of the opposite signs are mixed on spatial scales of tens to hundred kilometers. This is consistent with the results of *Klein Tank and Koennen* [2003] who analyzed linear trends in annual precipitation amount, annual number of very wet days (with daily precipitation higher than 95% threshold) and in the fraction of annual precipitation due to very wet days ($R95_{tot}$) for the period from 1946–1999 using ECA data collection. These indices cannot be directly compared to the p_{95} estimates used in our study [*Zolina et al.*, 2005], but they also do not show any clear spatial pattern of linear trends for Germany. For $R95_{tot}$ *Klein Tank and Koennen* [2003] report statistically significant trends only in 3 of 18 German locations. Their estimates of upward trends of 1.5 to more than 3% in $R95_{tot}$ in the southwestern Germany are qualitatively consistent with our estimates.

[17] Figure 5a summarizes the linear trend estimates derived from the annual records using occurrence histograms of trend estimates at different locations. Although influenced by the inhomogeneous station density, which is somewhat higher in the Central and Southern Germany compared to the Northern Germany, such a histogram gives quite a good overview of trend statistics. The histogram is peaked at slightly positive trend classes with the modal value lying within the range from 0 to 2% per decade. The number of locations with significantly positive and negative trends in heavy precipitation is 20% and 9%, respectively, of all stations.

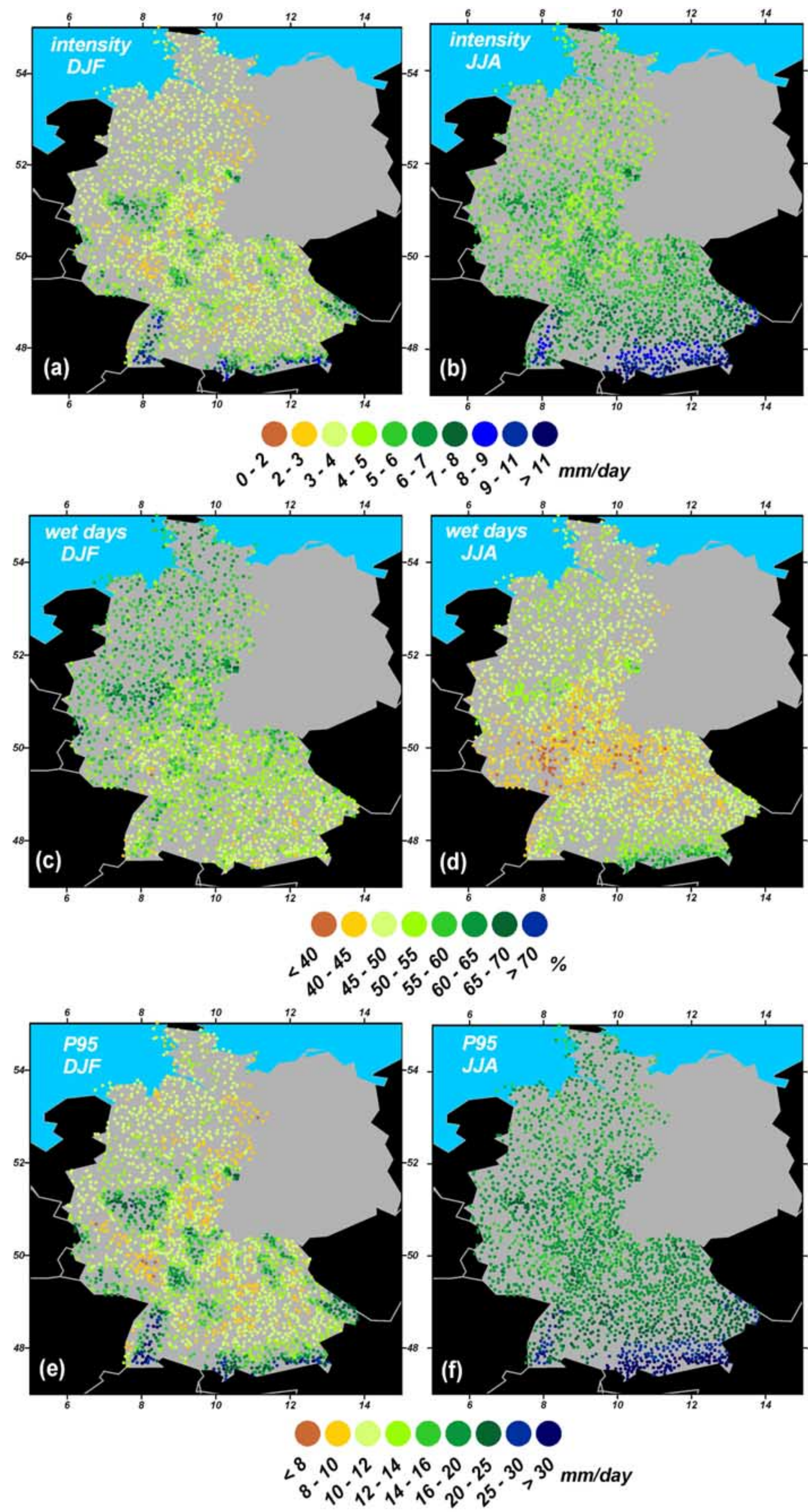

Figure 3. Climatological winter (DJF) (a, c, e) and summer (JJA) (b, d, f) precipitation intensity (mm/day) (a, b), occurrence of wet days (%) (c, d), and p_{95} (mm/day) (e, f).

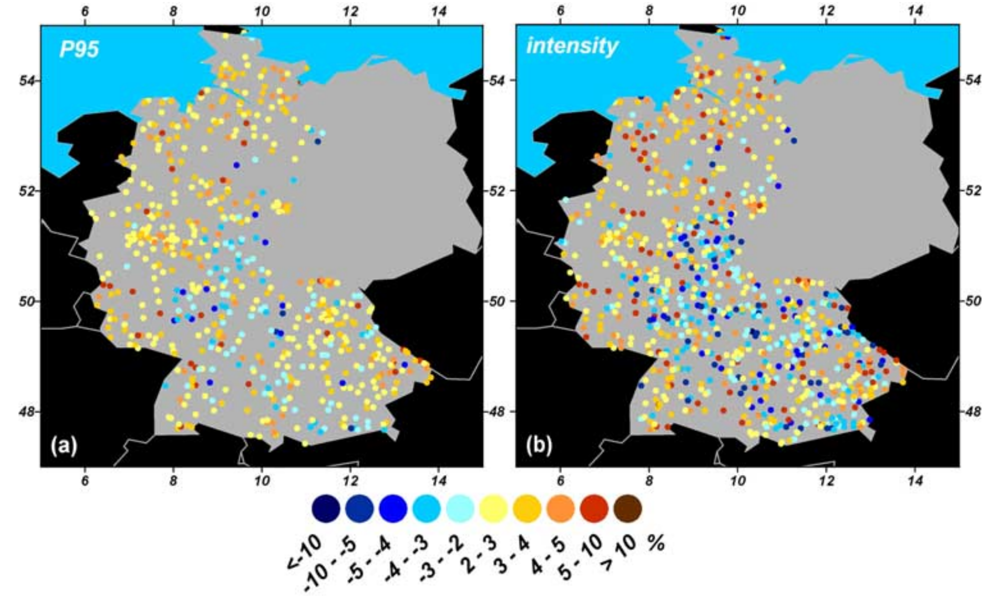

Figure 4. Linear trends (percent per decade) in the year-round estimates of 95%-percentile (a) and intensity (b) of daily precipitation over the Western Germany. Only the trends significant at 95% level according to *t*-test, Mann-Kendall test and Hayashi ratio are shown.

[18] Figure 6 show the linear trend estimates in p_{95} for different seasons. The winter season trend pattern (Figure 6a) shows everywhere positive trends over Northern and Western Germany. More than 1800 locations over Germany indicate positive trends and about 90 show downward tendencies. Positive trends at 95% significance level were obtained for 666 of the 2125 rain gauges considered. Only 17 locations indicate significantly negative linear trends in p_{95}, they are located in Southern and Southeastern Germany and do not show clustering on regional scale. The largest increases in p_{95} of more than 11% per decade are observed in Central Western Germany and in the southeastern mountain regions resulting in an increase of heavy precipitation of about 1.5–2.5 mm/day and 3–4 mm/day per decade, respectively. In Northern Germany positive trends in p_{95} range from 5 to 8.5% and from 1 to 3 mm/day per decade. The spring (MAM) trend pattern (Figure 6b) contains 264 locations of significantly positive trends in heavy precipitation. They are weaker than in winter with the largest upward tendencies (8–10% per decade) found in the mountain regions of Southern Germany, except the Alps, and near the western German border. Summer linear trends in p_{95} (Figure 6c) show in general opposite signs to those found for winter and spring with the strongest decreases of more than −7%

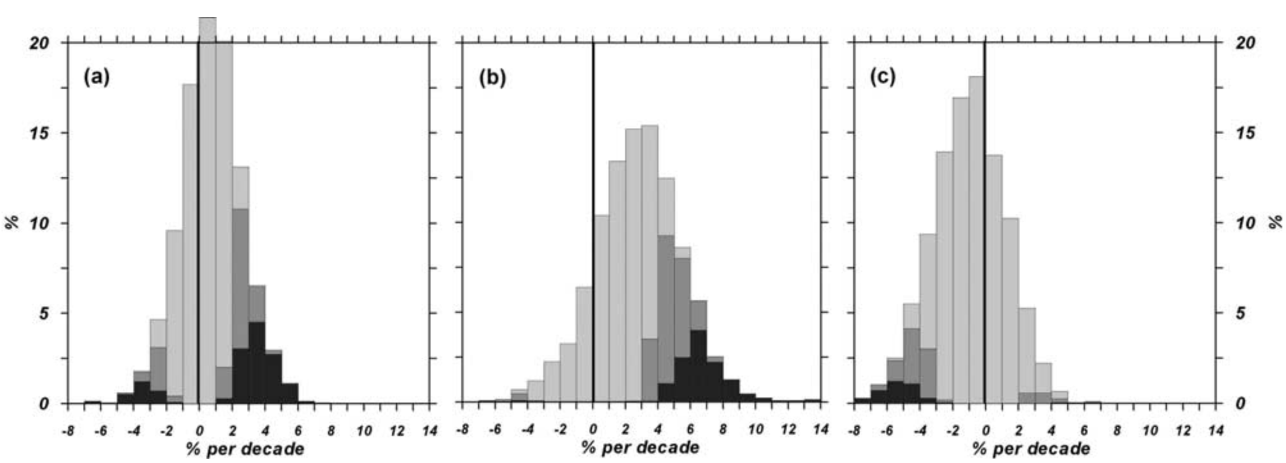

Figure 5. Occurrence histograms of the estimates of linear trends derived from year-round (a), winter (b) and summer (c) time series using all 2125 stations selected for the analysis over Western Germany. Statistical distributions of all trend estimates are shown in light grey, statistically significant trends are shown in dark grey, distribution of the locations where statistically significant trends were identified for all 25 periods (see text) are colored in black.

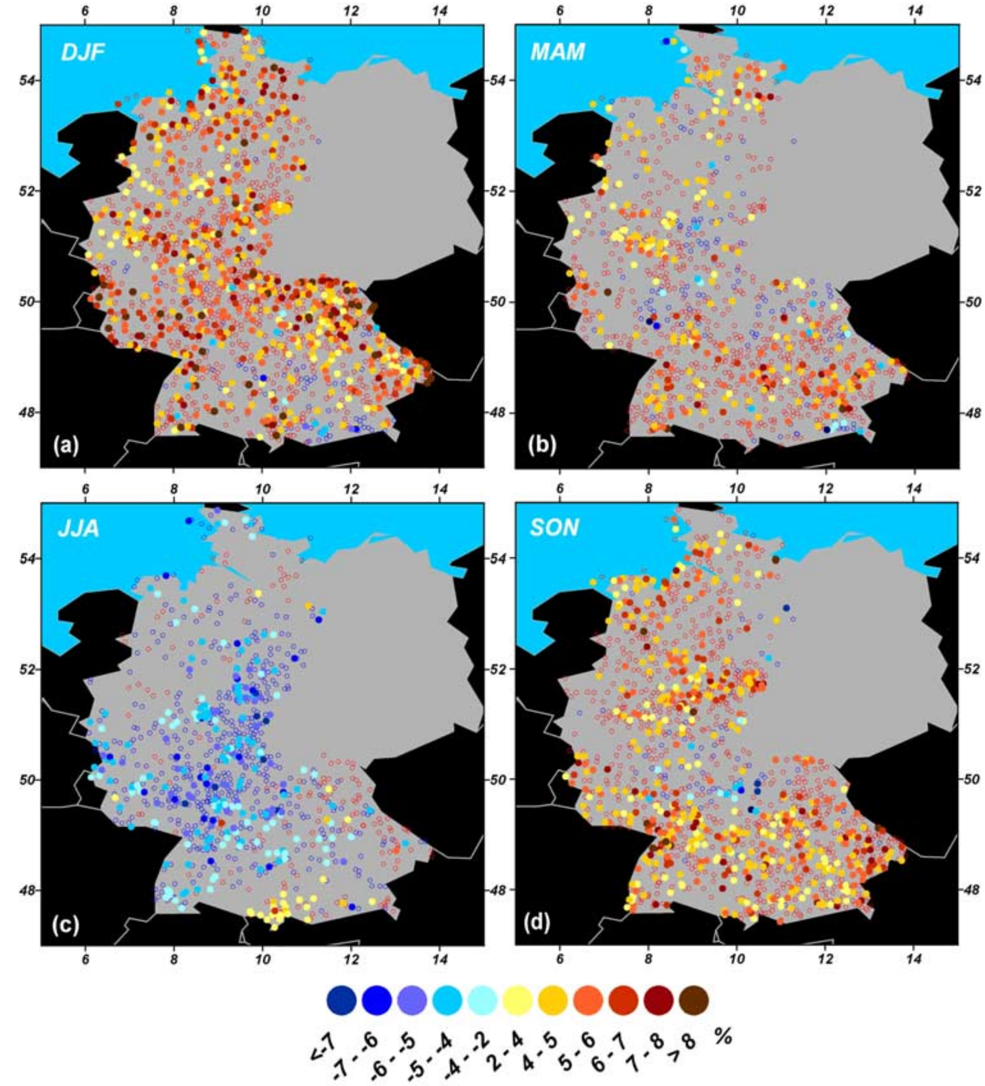

Figure 6. Linear trends (percent per decade) in 95%-percentile of daily precipitation for winter (a), spring (b), summer (c) and autumn (d). Small circles show all trend estimates and large circles denote the locations where the trends are significant at 95%, estimated as in Figure 4, for the period 1950–2004.

per decade (2–4 mm/day per decade) in the central part of Western Germany. About 1800 stations in total have negative linear trends and only 300 points exhibit positive linear trends. Statistically significant positive summer trends form the strongly localized cluster in Southern Germany with 2 to 4% increase per decade. During autumn (SON, Figure 6d) 496 locations show positive trends which are significant at the 95% level. The strongest positive trends with increases of 8 to 10% per decade occur in the mountain regions of Southwestern Germany corresponding to actual increases from 2.5 to 4.5 mm/day per decade. A strongly localized cluster of stations with negative changes during autumn is found in Central Western Germany near Burgbernheim (Bavaria); these autumn downward tendencies are as strong as the summer season trends ranging from 4 to 9% corresponding to about 3 mm/day per decade.

[19] Figures 5b and 5c show the occurrence histograms of the trend estimates for winter and summer, respectively. Compared to the histogram based on the annual estimates (Figure 5a), they exhibit clear positive and negative modal trend values respectively for winter (DJF) and summer (JJA). For winter the modal value is within the range of 3–4% per decade; 98% of the significant trend estimates indicate positive changes. The histograms for spring and autumn (no figure shown) indicate results very similar to the winter results. For the summer season the modal trend value is slightly negative and almost 90% of all significant trend estimates are negative.

[20] A comparative analysis of spectral estimates at very low frequencies before and after the removing the linear trends confirms the conclusion about seasonally dependent trends in heavy precipitation. Figures 7a and 7b show the locations where the difference in spectral power for the frequency range corresponding to periods from 45 to 65 years is significantly higher in the initial time series compared to those after linear trends were filtered out.

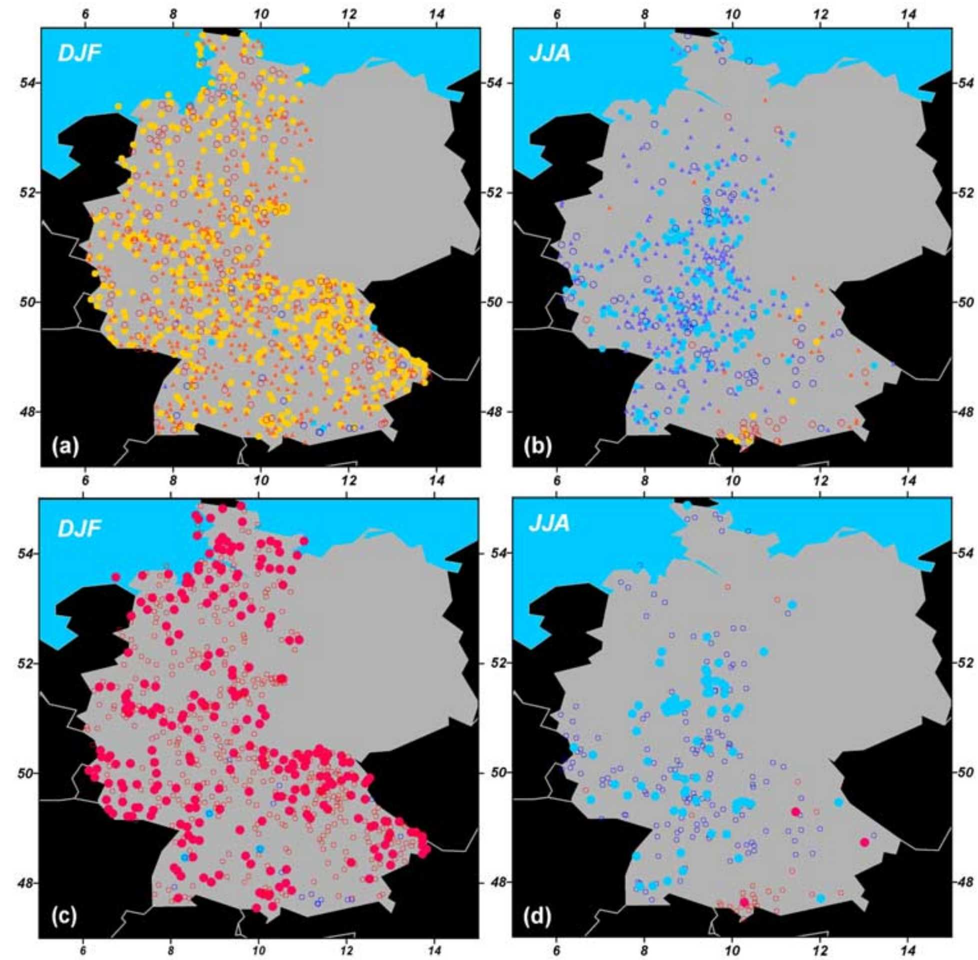

Figure 7. Locations where statistically significant linear trends in p_{95} values were simultaneously identified by spectral analysis at very low frequencies and by linear regression analysis (closed circles), by spectral analysis only (triangles) and by linear regression only (open circles) for (a) winter and (b) summer seasons. Locations where statistically significant linear trends in 95%-percentile of daily precipitation were identified for the period 1950–2004 (triangles, recalled from Figures 6a and 6c) and for all possible 25 periods starting during 1950–1954 and lasting until 2000–2004 (closed circles) for (c) winter and (d) summer.

Spectra were computed using autoregressive estimation and by Welch's method. For the winter season (Figure 7a) spectral analysis shows statistically significant differences at the 95% level for 926 locations. Of these locations 632 (i.e., nearly 96% of total number of 666) were identified by the linear regression analysis as those indicating significant linear trends. For the summer season (Figure 7b) spectral analysis confirms the presence of negative linear trends in 513 locations compared to 235 locations identified by the regression analysis. It is interesting to note, that the spectral analysis does not confirm the positive linear trends for the cluster of southernmost stations in the summer season. However, a similar spectral power analysis after removing of the 2nd order polynomial trends confirmed the presence of parabolic signals in p_{95} at 95% significance level for this cluster.

[21] In the following we assess the potential impact of the variable beginning and the ending years of the records on the estimates of linear trends, as mentioned in section 2. In order to assess the trend sensitivity to this effect we computed trends in p_{95} over shorter time series starting and ending within the first and the last 5 years of the period 1950–2004. The number of stations with significant trends of the same sign for different periods is summarized in Table 1. Locations which show significant (95% level) positive or negative trends for all 25 period variations are also shown in Figure 7c and d for winter and summer, respectively. Table 1 also shows estimates of the field significance for the trend patterns. These estimates were derived according to *Livezey and Chen* [1983] from the binominal distribution and according to the Walker test [*Wilks*, 2006]. They quantify the extent to which the beginning and the end dates of the records can affect the robustness of the seasonal trend patterns. The number of locations where trends of the same sign are significant at 95% level may change from one selected period to another quite considerably (e.g., from 21% to 40% of locations in winter). According to the results summarized in Table 1, however, the trend

Table 1. The Number of Locations Which Reveal Significant (95% Level) Trends for the 95%-Percentile of Daily Precipitation for Different Periods Starting Between 1950 and 1954 and Ending Between 2000 and 2004[a]

		2000		2001		2002		2003		2004	
1950	DJF	478***	20	415***	20	503***	20	581***	18	666***	17
	MAM	195***	29	198***	27	284***	12	261***	18	264***	19
	JJA	20	245***	26	284***	45	188**	33	230***	32	235***
	SON	345***	25	373***	20	478***	15	496***	17	496***	17
1951	DJF	581***	13	515***	15	625***	13	709***	12	800***	11
	MAM	199***	26	210***	26	295***	14	270***	17	271***	18
	JJA	25	201***	26	233***	41	146**	30	185**	30	188**
	SON	335***	24	379***	18	477***	16	499***	16	499***	16
1952	DJF	609***	12	529***	15	641***	12	731***	10	811***	7
	MAM	232***	36	239***	33	326***	16	301***	23	301***	24
	JJA	28	205***	35	236***	48	145	39	182**	39	185**
	SON	365***	20	401***	18	498***	12	519***	12	519***	12
1953	DJF	544***	12	457***	15	585***	13	672***	13	761***	8
	MAM	233***	27	245***	27	333***	13	317***	19	316***	19
	JJA	14	277***	12	329***	26	214***	25	264***	25	269***
	SON	412***	20	445***	15	557***	10	563***	12	563***	12
1954	DJF	429***	18	340***	22	480***	22	544***	15	635***	14
	MAM	246***	33	269***	34	366***	12	313***	25	316***	26
	JJA	12	289***	15	328***	31	207***	21	252***	21	261***
	SON	273***	28	311***	26	394***	15	422***	18	422***	18

[a]Since the data set ends in July 2004, that the JJA and SON estimates for the periods ending at the years 2003 and 2004 are identical. Normal font shows positive trends and italic font shows negative trends. Stars indicate the field significance at 99% level (***), 95% level (**) and 90% level (*).

patterns keep the field significance, substantiating the robustness of positive trends for winter, spring and autumn seasons and of the negative trends for the summer period. For all possible combinations of beginning and the end years the field significance of the pattern of positive trends for DJF, MAM and SON and negative trends for JJA estimated according to binary test of *Livezey and Chen* [1983] is higher than 95%, and in most cases it even exceeds the 99% level. The Walker test implies field significance at least at 95% level for all possible arrangements of the record periods. We also display in Table 1 the number of stations showing trends of the opposite (with respect to the dominant pattern for a given season) sign, i.e., negative trends for DJF, MAM and SON and positive trends for JJA. For each season we found just few locations where these trends are significant. No period for any season shows field significance for these trends. It is interesting to note that Figure 7d does not show the cluster of positive trends in summer in the Southern Germany. This is consistent with the analysis of spectra which indicated that the trends in this area are likely to be non-linear. The results shown in Figure 7 and Table 1 are also summarized in Figure 5, displaying the fraction of locations for which significantly positive and negative trends were identified for all 25 period lengths. For both the winter and summer seasons there are practically no locations with significantly negative or positive trends, respectively, for all 25 period lengths. For the annual time series, however, Figure 5a shows populations of locations for both positive and negative trends. Thus our trend estimates clearly show that secular changes in heavy and extreme precipitation over Central Europe indicate a clear seasonality being positive during winter, spring and autumn and clearly negative in summer.

[22] We have to note here, that estimation of the rate of family wise type I error using Walker test or similar to it Bonferroni-Sidak adjustment of individual significance tests [see, e.g., *Keppel and Wickens*, 2004] is, however, hardly directly applicable to our case. First, according to Bonferroni-Sidak adjustment a single p-value for n = 2125 should be lowered for each test to 0.000024. However, it is not a single estimate of positive/negative trend what can increase the rate of family wise error in our analysis, but rather a simultaneous occurrence of about 500–800 individually significant trend estimates of a total of 2125 tests. Moreover, the overall averaged correlation of data records is typically higher than 0.7 for our data and closely matches 0.90–0.95 for regions with a spatial scale of about 100 km. This implies that even a single p-value should be lowed to approximately 0.005. Tentative estimates performed for simultaneous occurrence of 600 individually significant trends of the same sign imply the necessity to lower p-value to about 0.01–0.02. The analysis of trend estimates significant at 99% level (no figure shown) reduces the number of locations where the trends are significant to e.g., 276 locations with positive trends in winter and to 71 locations with negative trends in summer. However, these patterns also hold the field significance. The discussion of problems concerning the direct application of Bonferroni-Sidak adjustment to similar cases in medical statistics can be found in *Perneger* [1998], *Morgan* [2007] and others.

5. Association of Trends in Extreme Precipitation Characteristics With Changes in Mean Precipitation and Impact of Seasonality on the Characteristics of Annual Cycle

[23] Figure 8 shows estimates of winter and summer linear trends in mean precipitation p, precipitation intensity p_i and the number of wet days. Winter to summer changes in the trend sign for both p and p_i are consistent with those for p_{95} (Figures 6 and 7). Patterns of positive/negative trends in winter/summer are somewhat more evident for precipitation intensity (638 and 408 points, respectively, with significant (95% level) positive/negative trends in winter/summer). The largest increase in precipitation intensity of 10–13 % per decade is observed in Northern

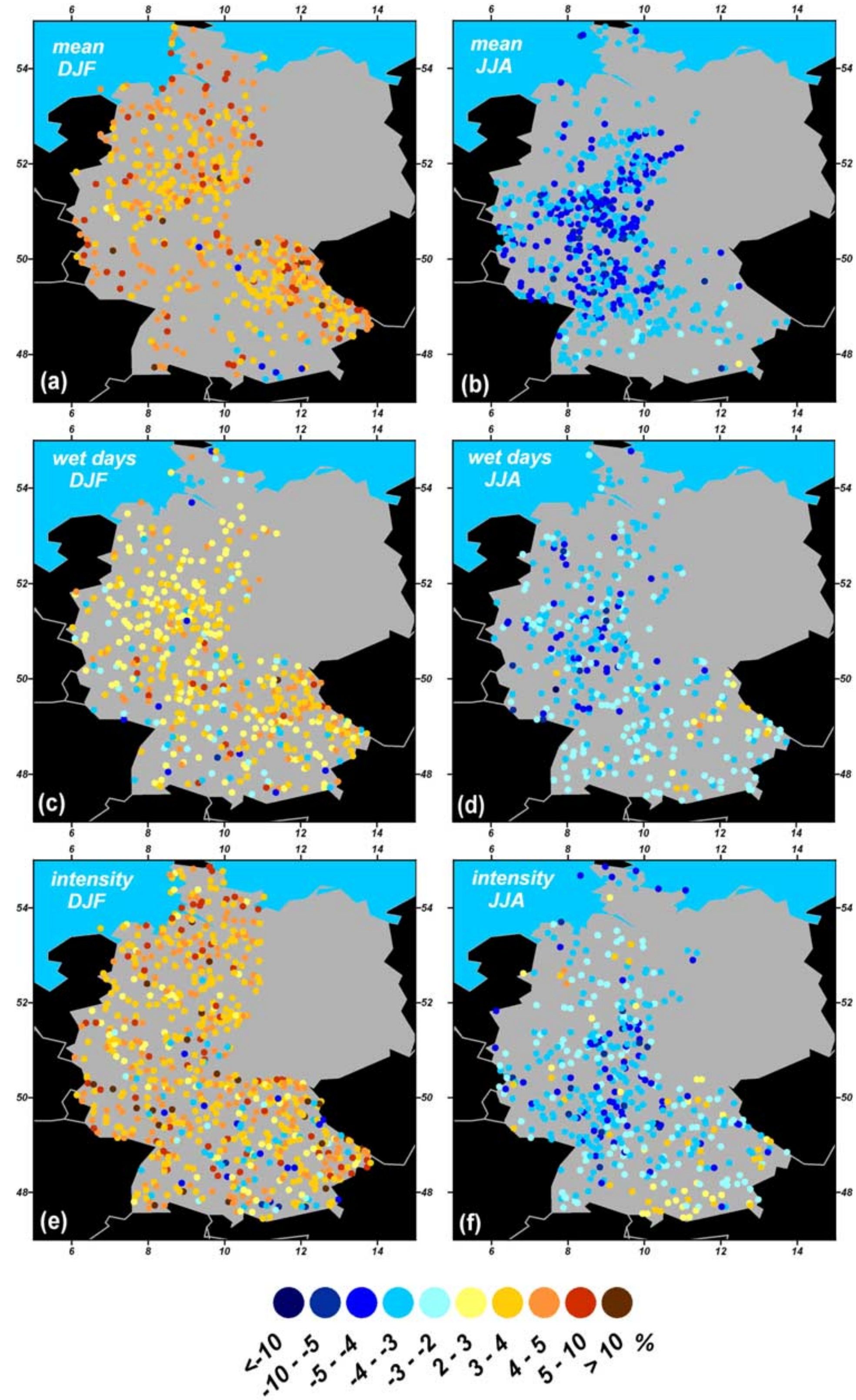

Figure 8. Linear trends (percent per decade) in mean precipitation (a, b), the number of wet days (c, d) and precipitation intensity (e, f) for winter (a, c, e) and summer (b, d, f). Trend significance is estimated as in Figure 6.

Germany. The strongest summer decrease in the Central German regions range from 8 to 11% per decade. For mean precipitation the number of stations with significant positive/negative trends for winter/summer seasons is only 510 and 397, respectively. The strongest positive and negative tendencies in mean precipitation exceeding 10% per decade are identified in Northern and Central Germany for winter and summer, respectively. Both mean precipitation and precipitation intensity trends indicate field significance at 95% levels. A similarly analysis of linear trends for the number of wet days (Figures 8e and 8f) shows positive tendencies with the largest magnitudes of 5–10% per decade (about 2–7 wet days per season and decade) during winter and opposite changes in summer, ranging from 3 to 10% per decade. Thus analysis of trends in mean precipitation, precipitation intensities and the number of wet days shows that linear trends in extreme precipitation are generally in line with trends in mean precipitation parameters in agreement with the regional study of *Hundecha and Bardossy* [2005].

[24] We now turn to the question whether the observed seasonality in extreme and heavy precipitation characteristics over Western Germany is also related to changes in weak and moderate precipitation. To this goal we estimated trends for the 10% quantiles of the fitted Gamma PDF of daily precipitation for selected regions. Quantifying of the role of different classes of precipitation intensities allows for identification of the so-called disproportional [*Easterling et al.*, 2000; *Groisman et al.*, 2005] changes in precipitation extremes. With some minor methodological modifications this approach was used by *Gershunov* [1998] and *Karl and Knight* [1998] for North American rain gauges, by *Brunetti et al.* [2004] for the Italian collection of daily station measurements and by *Zolina et al.* [2004] for a comparison of reanalyses with station data. We estimated linear trends for different classes of daily precipitation distribution in different regions over Western Germany. For most regions, in winter positive trends in heavy and extreme precipitation are associated with either negative or insignificant changes in the intensity of weak precipitation while during summer negative trends of the comparable relative magnitudes are observed for all classes of precipitation intensities. In Figure 9 we show the distribution of linear trends for different classes of precipitation intensities averaged over Western Germany. Although this figure (as well as Figure 5) is somewhat influenced by inhomogeneous spatial distribution of station density, it can be considered as representative for Germany, taking into account that for most regions diagrams are quite similar. The precipitation intensity of 70% and higher percentiles is characterized by statistically significant 2 to 3% decadal increase. This tendency is associated with a pronounced decrease of the intensity of weak precipitation (<20% percentiles) of more than 2% per decade. However, during summer season (Figure 9b) statistically significant negative trends are observed for all precipitation classes, ranging from 1.5% per decade for heavy precipitation to about 3.5% per decade for weak precipitation.

[25] Using fixed percentile bins (Figures 9a and 9b) of the fitted Gamma PDF (as well as the other distributions) limits the estimation of the relationships between the mean and extreme precipitation characteristics and, thus, may not be necessarily effective for the identification of disproportional changes [see, e.g., *Michaels et al.*, 2004]. Instead, *Michaels et al.* [2004] suggest analyzing precipitation changes during the 10 wettest days of the year. We have to note that this approach also has some limitations because 10 (or any other number of wettest days) represent typically different percentages of the total number of wettest days in different regions. For our case the 10 wettest days may represent from 14 to 30% of wet days in different regions. Moreover, time changes in the number of wet days of 6 to 10% per decade (Figure 9), also result in an additional uncertainty of 3–6% in the percentage which represent the 10 wettest days of the total number of wet days. Nevertheless, following *Michaels et al.* [2004] we computed the relative changes in precipitation for the 10 wettest days (Figures 9c and 9d). During the winter season (Figure 9c) positive linear trends were identified for all 10 wettest days with more than 3.5% per decade for the first and about 2.5% per decade for the 10th wettest day. However, the percentage of precipitation during the 10 wettest days in winter ranges from 35 to 80% of the seasonal precipitation total with an average of 57%. Thus this amounts lies within the classes above the 40% percentile in Figure 9a and does not contradict with the conclusion of the stronger changes in heavy precipitation compared to the weak precipitation in winter. During summer (Figure 9d) the analysis of linear trends for the 10 wettest days generally supports the finding of Figure 9b, and shows a decrease from 1.6% per decade to 3.2% per decade in precipitation from the 1st to the 10th wettest day.

[26] The strong seasonality should imply that during the last 55 years annual amplitudes of heavy and extreme precipitation have decreased over Western Germany. Mean seasonal precipitation estimates over Europe show 1.5 to 2.8 times higher summer precipitation totals compared to winter values [*Zveryaev*, 2004]. We estimated "winter minus summer" differences for different precipitation characteristics which roughly quantify the amplitude of the annual cycle. Given only 4 seasonal estimates per year, it is difficult to apply techniques based on the harmonic analysis to detect the annual amplitude. Figures 10a and 10b show the mean "summer minus winter" differences in precipitation intensity and p_{95} values. Maximum winter-to-summer change of precipitation intensity Δp_i of more than 5–6 mm/day (up to 60% of the mean values) is observed in the Southern Germany. The smallest range of seasonal variations of less than 1 mm/day is typical for the western part of Central Germany. The spatial structure of the seasonal difference in heavy precipitation (Δp_{95}) is quite similar to the one of Δp_i with the largest winter-to-summer changes identified in the southernmost mountain regions (more than 20 mm/day) and the smallest annual range of about 2–5 mm/day observed in Central Germany. Estimates of Δp_{99} (not shown) are 30 to 50% larger than for Δp_{95}, displaying a very similar spatial structure. Linear trends in winter-to-summer differences Δp_i and Δp_{95} over the period 1950–2004 are presented in Figures 10c and 10d. Over Western Germany the annual range in extreme and heavy precipitation has decreased between 1950 and 2004 by 30–60%. The largest linear trends in Δp_{95} of about 2–3 mm/day per decade are observed in the southwestern and central eastern parts. This is consistent with significant negative trends in Δp_i characterized by the

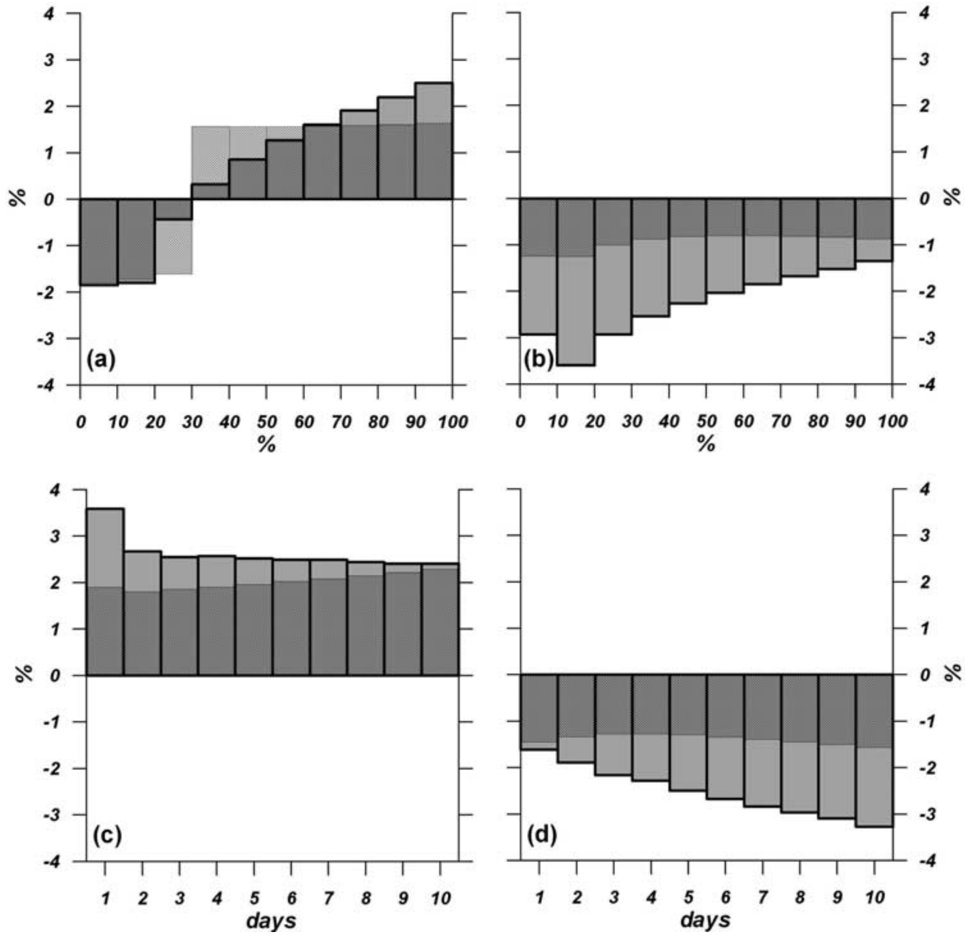

Figure 9. Linear trends (percent per decade) in the precipitation intensity for different precipitation classes averaged over all stations selected for the analysis for winter (a) and summer (b) seasons and linear trends (percent per decade) in the precipitation intensity for the 10 wettest days averaged over all stations for winter (c) and summer (d). Shaded bars indicate trend significance at 95% level.

largest decrease of 0.5–1 mm/day per decade found in Central German regions.

6. Summary and Discussion

[27] The updated collection of DWD daily rain gauges implies a strong seasonality in the linear trends of precipitation characteristics over Western Germany. Heavy and extreme precipitation, quantified by the 95% and 99% percentiles respectively, indicate upward changes from 5 to 13% per decade in winter, spring and autumn and negative tendencies of 3 to 9% per decade during summer. Estimates of field significance show that the found seasonality is insensitive to including or excluding the first and the last several years of the records. Seasonality is also clearly visible in secular changes of the mean precipitation. During winter the relative change in the intensity of heavy precipitation is stronger than for moderate precipitation classes and can be associated with a decreasing intensity of weak precipitation. Alternatively, in summer, negative changes affect all classes of precipitation intensity. Our results also demonstrate that estimates of climate variability in precipitation characteristics based on annual time series [e.g., *Groisman et al.*, 2005; *Klein Tank and Koennen*, 2003] result from the unequal changes of opposite signs in different seasons. Considering linear trends and their seasonal dependence using 55-year data records, we cannot certainly attribute the trends to secular changes, which are typically associated with the longer (i.e., centennial) scales and represent the climate change signals due to anthropogenic warming [*Trenberth et al.*, 2007]. Nevertheless, our analysis shows that during the last 55 years changes in heavy precipitation represent predominantly linear tendencies influenced only to a minor degree by higher order polynomial signals. Thus they are consistent, with the longer time estimates of linear trends reported by *Zolina et al.* [2005] and *Moberg et al.* [2006]. Nevertheless, using only 55 years of data we cannot attribute these trends unconditionally to secular changes, assuming that different signal could be observed before 1950s.

[28] Seasonality in extreme precipitation may originate from changes in the dominant circulation modes during different seasons. Clearly, the North Atlantic Oscillation (NAO) dominates the cold season spanning the period from November to March [*Hurrell*, 1995], while the warm season

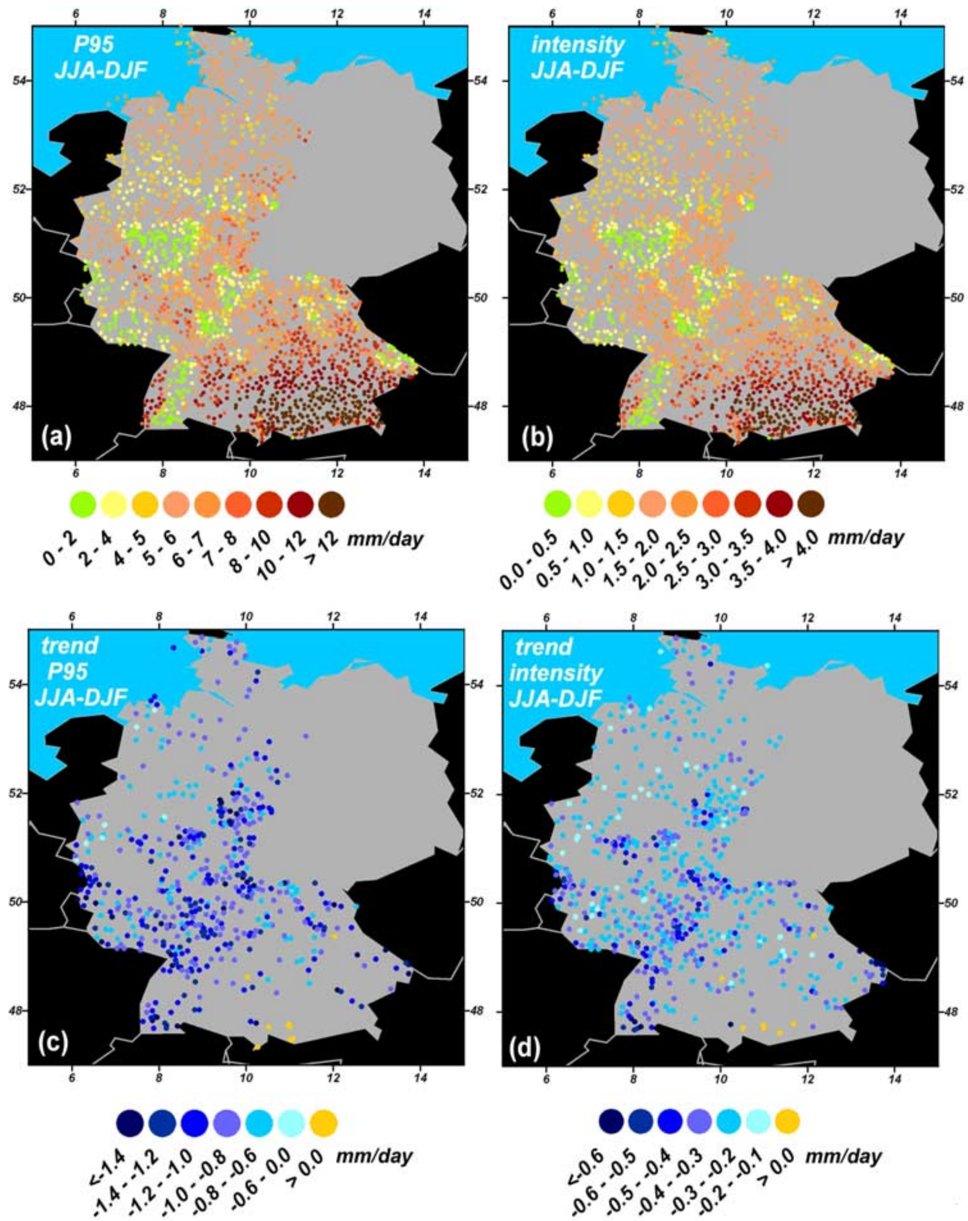

Figure 10. Climatological summer minus winter differences in heavy precipitation (Δp_{95}) (mm/day) (a) and in precipitation intensity (Δp_i) (mm/day) (b) as well as linear trends (mm/day per decade) in Δp_{95} (c) and Δp_i (d). Only the trends significant at 95% level according to the same criteria as in Figure 6 are shown.

circulation in the Atlantic-European sector is largely dominated by the other modes. Besides the East Atlantic Pattern (EAP) [*Barnston and Livezey*, 1987], the circulation is also influenced by the Scandinavia – Southwestern Europe dipole in 500 hPa height [*Zveryaev*, 2004, 2006]. *Sutton and Hodson* [2005] and *Zveryaev* [2006] argued that the boreal summer climate is strongly modulated by the Atlantic multidecadal oscillation (AMO). Different long-term tendencies in the intensity of these circulation modes during different seasons may be responsible for the seasonality in changes of extreme precipitation. On the other hand, we can also expect seasonal changes in the intensity of local mechanisms forming extreme precipitation in different European regions. These mechanisms can be in particular associated with the land use change, that was the case over the last decades in the Rhein river basin. Moreover, taking into account that extreme precipitation, unlike mean precipitation, is strongly constrained by the atmospheric moisture content [e.g., *Allen and Ingram*, 2002], we expect a stronger spatial differentiation of extreme precipitation characteristics in the summer compared to winter. In this respect, it is important to understand whether seasonality represents a regional Central European feature or a pan-European phenomenon.

[29] In our work a clear evidence of seasonality was drawn from a very dense network, which is not yet available for the whole Europe. An analysis based on the

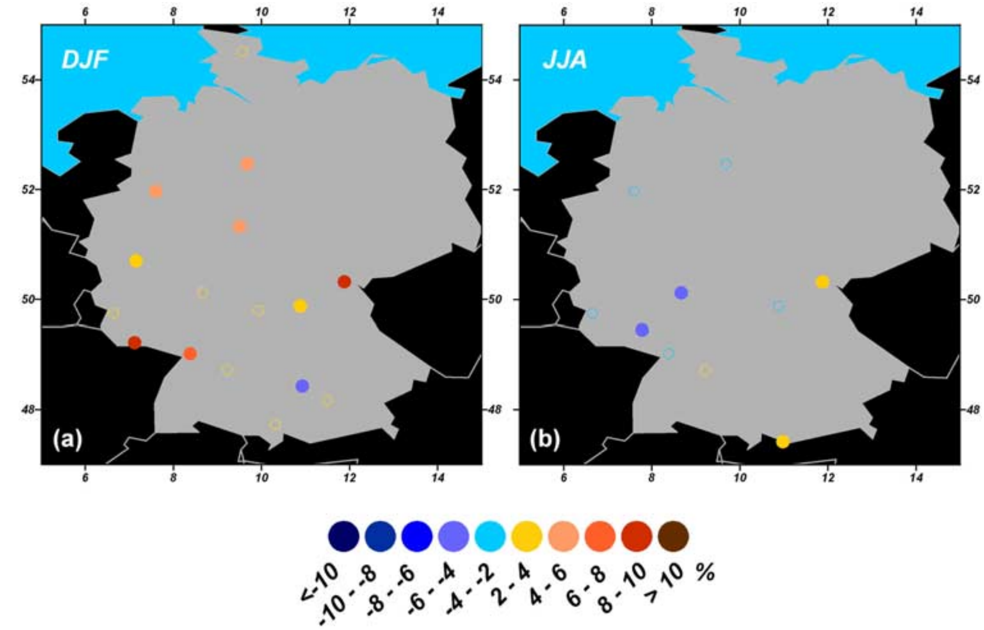

Figure 11. Linear trends (percent per decade) in 95%-percentile of daily precipitation for winter (a) and summer (b) derived from ECA collection of rain gauges. Trends significant at 90% level are shown by closed circles.

station data from high quality but quite coarse resolution collections, such as the ECA collection [*Klein Tank et al.*, 2002], indicated a seasonality of secular changes in heavy and extreme precipitation for 100-year time series (1900–2000) in few locations of Central Western Europe [*Zolina et al.*, 2005]. *Moberg et al.* [2006] reported for the period 1901–2000 an intensification of mean and extreme precipitation in winter ranging for Central Europe from 5 to10% per decade. At the same time, summer trends were close to zero and statistically insignificant. We selected from the ECA collection the 25 stations covering our analysis area. These are the so-called synoptic meteorological stations for which the observational practice is different from climate and rain gauge observation stations and characterized by more strict guidelines. Figure 11 shows estimates of the linear trends in p_{95} derived from these stations. The trend signs in p_{95} are primarily positive in winter and primarily negative in summer. However, in winter positive trends at 90% level of 4 to 10% decade are observed for 8 locations. This does not guarantee the field significance even at the 90% significance level according to both the binary and the Walker test. Remarkably, in summer, significantly negative at 90% level trends in heavy precipitation were identified in only 2 of 25 locations. These estimates are in agreement with *Klein Tank and Koennen* [2003] who noted quite noisy patterns of linear trend estimates using the ECA collection. Thus the high quality ECA collection cannot be used for testing seasonality in secular changes of precipitation characteristics due its coarse resolution. In this sense, the one possible line of extension for this study is the incorporation of higher resolution collections from different European countries [e.g., *Auer et al.*, 2005; *Efthymiadis et al.*, 2006]. Alternatively, long-term time series from global and regional reanalyses can be considered, but their precipitation characteristics are known to be biased compared to the station data [e.g., *Zolina et al.*, 2004]. Recently *Scheifinger et al.* [2006] reported strong biases in Regional European Model (REMO) precipitation characteristics in the Alpine region for the period from 1971 to 1999. Moreover, estimates of long-term tendencies using reanalyses may be influenced by the changing input to data assimilation. Thus precipitation products from numerical weather prediction systems should be first extensively validated before they are used for the analysis of seasonality in long-term variability of European precipitation.

Appendix A: Observational Techniques, Instrumentation and Quality Control in DWD Data Collection

[30] The rain gauge network of the German Weather Service (DWD) is one of the densest and most properly maintained regional precipitation networks. It consists of 11617 stations of which 5454 have been digitized, controlled and included into the digital database (MIRAKEL-Datenbank) while the other 6163 are still in process of continuous preprocessing at DWD and its partners. All DWD precipitation stations are equipped with the HELLMANN rain gauges with a collecting surface of 200 cm^2. All rain gauges used are shielded with a special cover to protect from evaporation and equipped with built-in heating devices controlled by thermostats including power supply units. These devices are typically activated in the beginning of the cold season, when each instrument is additionally supplied by the snow cross and an additional lid. These prevent a possible out sore of the pleased snow. For snow precipitation the water level of the melted precipitation is calculated as a precip-

itation level. The rain gauges are installed and exposed in a way, that their collecting surface is 1 m over the ground. The accuracy of precipitation measurements at every rain gauge is 0.1 mm. In the late 1990s manual reading procedure at DWD rain gauges has started to be continuously changed to automatic one by installation of PLUVIO devices. These provide estimates of daily precipitation based on the control weighting. Implementation of this transformation of the reading did not implement change of time to which the reading is attributed.

[31] Precipitation measure occurs daily at 07:30 local time, corresponding to CET. Every month the daily records are transmitted to the regional pre-processing offices, where they are checked by quality control operators. Finally the data are transferred from the regional centers to DWD headquarters at Offenbach, where they are digitized, repeatedly checked for quality and undergo correction procedures. These corrections include adjustment of the reading time (if possible) and account for the instrument exposition. The result of the correction is indicated by quality flags supplied with the final digital records. For the majority of stations the flags read "0", implying "repeatedly checked, no errors remained". However, the corrections applied did not include wind correction. A proper application of wind correction [*Sevruk*, 2000; *Nešpor and Sevruk*, 1999; *Michelson*, 2004; *Sieck et al.*, 2007] requires wind measurements explicitly co-located in space and time with the rain gauge data. However, wind is measured exclusively at the so-called synoptic stations (about 300 locations over Germany) of which just about less than half overlap in time with rain gauge data. Application of wind correction for these stations only would result in a bias associated with the different data processing at about 7% of stations. Wind-associated errors in rain gauge readings range from 4 to 15% for low precipitation to 1–4% for high precipitation dependent on wind speed [e.g., *Nešpor and Sevruk*, 1999; *Michelson*, 2004]. These estimates give a tentative range of uncertainties implied by the omitted correction for wind speed. This uncertainty has a smaller impact on heavy and extreme precipitation studied in our work, compared to small and moderate precipitation. Taking into account that this correction was not done for the data, we imposed quite strict statistical tests of the trend signals.

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S. Bachner, A. Kapala, C. Simmer, and O. Zolina, Meteorologisches Institut, Universitaet Bonn, Auf dem Huegel, 20, Bonn, D-53121, Germany. (olga.zolina@uni-bonn.de)

S. Gulev, P.P. Shirshov Institute of Oceanology, Moscow, Russia.

H. Maechel, Deutscher Wetterdienst, Offenbach a.M., Germany.