Changes in the Duration of European Wet and Dry Spells during the Last 60 Years

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ABSTRACT

Daily rain gauge data over Europe for the period from 1950 to 2009 were used to analyze changes in the duration of wet and dry spells. The duration of wet spells exhibits a statistically significant growth over northern Europe and central European Russia, which is especially pronounced in winter when the mean duration of wet periods increased by 15%–20%. In summer wet spells become shorter over Scandinavia and northern Russia. The duration of dry spells decreases over Scandinavia and southern Europe in both winter and summer. For the discrimination between the roles of a changing number of wet days and of a regrouping of wet and dry days for the duration of the period, the authors suggest a fractional truncated geometric distribution. The changing numbers of wet days cannot explain the long-term variability in the duration of wet and dry periods. The observed changes are mainly due to the regrouping of wet and dry days. The tendencies in duration of wet and dry spells have been analyzed for a number of European areas. Over the Netherlands both wet and dry periods are extended in length during the cold and the warm season. A simultaneous shortening of wet and dry periods is found in southern Scandinavia in summer. Over France and central southern Europe during both winter and summer and over the Scandinavian Atlantic coast in summer, opposite tendencies in the duration of wet and dry spells were identified. Potential mechanisms that might be responsible for the changing durations of wet and dry periods and further perspectives are discussed.

1. Introduction

Rising intensities of mean and heavy precipitation over Europe during the last decades have been documented in many studies (Klein Tank and Können 2003; Zolina et al. 2005, 2009; Groisman et al. 2005; Moberg et al. 2006; Alexander et al. 2006). More detailed studies also confirm these tendencies for certain regions of
For a proper characterization of the observed changes, however, the duration of continuous periods with significant daily rainfall (wet spells) is as important as the standard metrics such as intensity, precipitation totals, number of wet days, and extreme precipitation statistics. Obviously the same precipitation intensity, precipitation total, and number of wet days will have quite different effects when the wet days are homogenously distributed in time or concentrated in a few wet periods (WPs). For instance, hazardous European floods are typically associated not with extreme rainfall events of short duration but, rather, with continuous periods of persistent heavy or even moderate precipitation (Mudelsee et al. 2003, 2004; Ulbrich et al. 2003a,b; James et al. 2004; Norbiato et al. 2007; Gaume et al. 2009). Furthermore, the duration of wet periods is very naturally associated with the duration of dry periods (DPS), which might be related to heat waves and/or droughts. Wet and dry spells together build the intraseasonal structure of the European hydroclimate.

Starting from the pioneering work of Mindling (1918), the importance of precipitation duration has been recognized in engineering hydrology for a long time. The time intervals considered were, however, primarily restricted to durations of minutes to hours (Weiss 1962; Sanson 1995; Madsen et al. 2002; McCuen 2005; Raftery et al. 2007; and others). Less attention has been paid so far to the analysis of long-term variability of the duration of wet and dry spells, which are characterized by continuous sequences of days with or without significant rainfall. According to Schmidli and Frei (2005), the duration of wet spells increased over the Swiss Alps during the twentieth century. Wibig (2009) reported a similar tendency over Poland for the last 50 years. Kuglitsch et al. (2010) reported that both duration and number of heat waves over the eastern Mediterranean region considerably increased starting in the 1960s. Analyses based on monthly estimates of the Palmer drought severity index (PDSI) hint at an increase of drought areas over Europe during the last century (e.g., van der Schrier et al. 2006), which may in some regions go along with increasing areas of moisture surplus (Dai et al. 1998). Recently Zolina et al. (2010) performed a pilot study concerning the temporal structure of European precipitation and concluded that during the period from 1950 to 2008 wet spells became longer and contained increasingly stronger precipitation extremes.

Over the continental United States (excluding Alaska) differences in the interannual behavior of heavy rainfall intensity for different rain durations were found by Kunkel et al. (1999, 2003), who considered consecutive series of both dry and wet days. A decreasing occurrence of long-duration storms during 1948–2004 across the United States was reported by Brommer et al. (2007). The comprehensive study of Groisman and Knight (2008) shows an increase of both duration and occurrence frequency of warm season dry day episodes over the contiguous United States during the last several decades. The recent study of Groisman et al. (2012) analyzed the increase in heavy, very heavy, and extreme event frequency and indirectly indicates an increase of WP durations over the central United States. Structural changes of precipitation were also reported for other continents. Recently Llano and Penalba (2011) found an increasing occurrence of extremely long dry periods (dry spells) in Argentina. Changing durations of wet and dry spells in northern Africa, associated with different climate types, were reported by Born et al. (2008).

Results from global and regional model simulations of the future climate also argue for the importance of accurate analyses of wet and dry periods. Besides projected changes in frequency and intensity of precipitation extremes (Semenov and Bengtsson 2002; Emori and Brown 2005; Scaife et al. 2008; and others), a number of studies using regional climate models suggest changes in the structure of European precipitation in the future climate (Beniston et al. 2007; May 2008). May (2008) for instance found, from simulations with the regional High-Resolution Limited-Area Model (HIRLAM), an increased length of dry spells in summer while wet spells become longer in winter and generally shorter in summer.

The analysis of wet and dry period durations is more complicated and requires higher quality observational data compared to analyses not addressing temporal sequences. First of all, the estimation of WPs and DPS puts quite strict requirements on data completeness because missing values may significantly influence estimates of event duration and the character of their alternation. Second, when analyzing changes in the duration of WPs and DPS, we typically deal with very limited event statistics compared to, for example, the exact number of wet or dry days. This makes it difficult to develop credible duration statistics from the raw data and requires the analysis of theoretical distributions, especially for characterization of the rare longer-term wet and dry spells.

In this study we analyze changes in the duration of wet and dry periods over Europe during the period from 1950 to 2009 using daily data from nearly 700 European rain gauges. Our main task is to quantify long-term
tendencies in the mean duration of WPs and DPs as well as in the occurrence of longer wet and dry spells. Section 2 describes the data collection used and the preprocessing of rain gauge records including accounting for missing values. In section 3 we present appropriate statistics for wet and dry periods. Reference climatologies of statistical characteristics for European wet and dry spells for the warm and cold halves of the year are presented in section 4. In section 5 long-term tendencies in the duration of wet and dry spells are analyzed, and in section 6 potential contributions of the changing number of wet days and the altering of wet days to these changes are discussed. Section 7 presents a summary and conclusions, and section 8 discusses potential mechanisms for the observed changes and future avenues of research.

2. Rain gauge station data and preprocessing

a. European rain gauge daily observations

Daily rain gauge observations were taken from the recently updated European Climate Assessment (ECA) dataset. Details of the ECA composition are given in Klein Tank et al. (2002), Klein Tank (2007), and Klok and Klein Tank (2009). In the earlier release of the ECA, 57 stations over European Russia, Belarus, and the Ukraine contained erroneous artifacts for the 1990s and 2000s owing to incorrect record decoding. In the updated release the original data from the Russian Hydrometeorological Service (RHS) collection were substituted for these recordings, and 32 new RHS stations were added. Zolina et al. (2005) argued for a maximum of 30% missing daily precipitation values for an unbiased estimation of trends in extreme precipitation. Estimations of wet and dry period durations, however, require more strict measures for data completeness. Sensitivity experiments by Zolina et al. (2010) show that unbiased estimates of WP and DP durations require records that miss less than 10% of daily values. From the 1558 stations of the collection only 699 records satisfy this requirement and these were used for the analysis discussed below. From the omitted 859 stations (57% of the total) 78% (670) were excluded owing to a significant number of missing years in the beginning and/or in the end of the records and 22% (189) due to the large number of gaps. The observations cover the period 1950–2009 and have the highest density in western Europe and Scandinavia. Figure 1 shows the locations of the 1558 stations available from the merged collection, including the 699 stations used in our analysis. The selected stations are quite inhomogeneously distributed over Europe with the highest sampling density in the Netherlands (261 stations) and southern Scandinavia (139 stations), which together contribute about 57% of the total number of stations. At the same time, Poland, the Czech Republic, Slovakia, Hungary, Bulgaria, and Greece remain practically unsampled in the ECA collection, which makes it difficult to produce any confident estimates for precipitation variability in these regions. Russia, the Ukraine, and the Caucasian states (which can be ranked as moderately sampled, similar to most western European countries except for the Netherlands and Norway) are formally densely populated with daily observing rain gauges; however, our check for record completeness results in only about 14% of usable stations (115 of 800). Given this strong inhomogeneity in station distribution, we perform estimates for the regions characterized by similar sampling conditions. These results should, however, be interpreted differently for different regions. Our conclusions for the Netherlands or Norway should not be considered an overemphasis of these regions, constituting together less than 1% of Europe as a whole and a few percent of western Europe. Rather, they provide the most robust estimates of WPs and DPs in well-sampled (although small in area) regions.

Recently, Haylock et al. (2008) developed a gridded 0.25° resolution product of European daily precipitation and other climate variables (e.g., van den Besselaar et al. 2011) based on the ECA collection. Although useful for a variety of applications, these data were not used in our study since they were produced using interpolation procedures to fill unsampled grid cells. Furthermore, gridded data imply a scaling difference between station point values and gridded area averages. This may seriously affect the accuracy of the analysis of wet and dry periods, especially in poorly sampled areas. Another possibility for enriching the collection is the inclusion of the Deutscher Wetterdienst (DWD) collection of about 6000 stations with a density even higher than in the Netherlands (Zolina et al. 2008). However, this collection is not part of the ECA dataset, and important quality control checks and homogenization procedures for this collection do not fit those applied to the ECA dataset.

b. Preprocessing and strategy

In this study, wet periods were quantified following Zolina et al. (2010) as consecutive days with significant precipitation (>1 mm day⁻¹). This threshold excludes very light precipitation and partially accounts for the limited accuracy of rain gauges (Klein Tank and Können 2003). A similar threshold is applied in many precipitation studies over Europe and the United States (e.g., Brunetti et al. 2004; Groisman et al. 2005; Alexander...
et al. 2006). We have to stress that the use of time series including light precipitation challenges the robustness of the results. Besides the high random observational errors for light precipitation, the observational practices for light precipitation also differ among European countries, which may result in artificial regional biases in multinational data collections such as the ECA. For this reason, we used the threshold of 0 mm day$^{-1}$ (no reported precipitation) as the definition of DPs. Here we differ from Groisman and Knight (2008), who applied a 1 mm day$^{-1}$ threshold for identification of dry spells.

We have to note here, however, that the thresholds used (>1 mm day$^{-1}$ for WPs and 0 mm day$^{-1}$ for DPs) may still imply uncertainties for the estimation of WP and DP durations. The definition of zero precipitation may be different among countries; in some, traces of precipitation are also reported as 0 mm day$^{-1}$. Furthermore, this definition could change over time because of the change to metric units (as in the United Kingdom) and changes in rain gauge design (as in Finland). However, the use of the alternative threshold of 1 mm day$^{-1}$ for European stations also results in uncertainties due to the low accuracy of light precipitation observations. We performed sensitivity tests for the threshold of 1 mm day$^{-1}$ and assured ourselves that results over most of Europe may change quantitatively, but not qualitatively. Some additional uncertainties in the estimation of WP and DP durations may be associated with solid precipitation during winter, especially in northern and eastern Europe (e.g., Nespor and Sevruk 1999; Bogdanova et al. 2002; Biemans et al. 2009). We believe that these, and other, inhomogeneities in the amount of measured frozen precipitation should not affect WP and DP duration statistics that are the major focus of this paper.

To quantify seasonal changes in the duration of WPs and DPs we performed separate estimates for the periods October–March (cold season) and April–September (warm season). We also tested alternative season choices (November–April and May–October), but for most locations results were similar, including our conclusions about

![Fig. 1. (a) Locations of 1558 European rain gauge stations available from the ECA collection for the period from 1950 to 2010 (green small dots) and of 699 stations finally selected for the analysis (larger red dots). (b),(c) Zoomed maps for the densely sampled Netherlands and Scandinavia. Regions for which we estimated parallel tendencies in the duration of wet and dry spells are contoured in blue in (a).](image)
interannual and interdecadal variability. Groisman and Knight (2008) defined the “warm season” as the period characterized by daily mean air temperatures above 5°C, but they focused on dry spells during the warm season. The use of a unique temperature threshold over Europe would be quite complicated since the duration of a period with daily temperature exceeding a given threshold (e.g., 10°C) may change from several weeks to 8–9 months depending on the region. Furthermore, temperature data are available at considerably fewer stations (compared to precipitation records) in the ECA collection. Thus, so as to compare results derived for individual years and to properly apply statistical procedures, we based our analysis on fixed seasons. The use of shorter periods, like the classical three-month seasons, would lead to considerable uncertainties when estimating the durations of WPs and DPs, which would then much more frequently cross or overlap the season boundaries. In all computations hereafter, WPs and DPs extending from March into April and from September into October were attributed to the seasons within which they started. In other words, if the WP started on 31 March and lasted 10 days, it was classified as belonging to the October–March period and was not included in the statistics for the April–September period. Most results will be presented for all of Europe. However, given the spatial inhomogeneity in station density, we also performed our analysis separately for five regions with a similar sampling density (Fig. 1): southern Norway (139 stations); the Netherlands (261 stations); France (32 stations); central southern Europe including the Balkan States, Romania, and Bulgaria (19 stations); and eastern Europe including Russia, Belarus, the Ukraine, and the Baltic States (53 stations).

3. Methods

a. Statistical distributions of wet and dry spell durations

The analysis of wet and dry period durations is highly sensitive to the continuity of records. Zolina et al. (2010) used annual records for the estimation of WP duration. When seasonal changes are considered, sampling may seriously affect the results. Furthermore, the estimation of statistics of very long wet and dry periods may become highly uncertain when performed using durations quantified directly from observations. Similar problems affect the analysis of precipitation intensities when statistics are based on observational data records whose completeness is frequently insufficient (the so-called empirical precipitation indices, Klein Tank and Können 2003). An alternative is the fitting of continuous theoretical probability density functions (PDFs) to the data. For instance, a Gamma distribution is typically used for the analysis of daily precipitation (e.g., Groisman et al. 1999; Wilks 1995; Zolina et al. 2004). Different extreme value distributions (EVDs) described by the generalized extreme value (GEV) distribution are applied for the analysis of precipitation of rare occurrences (Kharin and Zwiers 2000; Maraun et al. 2010b). Special distributions are used for the estimation of relative extremeness, that is, precipitation due to the most wet days (Zolina et al. 2009). Theoretical distributions appropriate for the duration of WPs and DPs belong to the family of discrete distributions since period lengths are counted in whole days (for daily data). Most frequently such distributions are approximated by a geometric distribution, but, depending on the definition of the event and on the region, other types might be applicable such as the mixed geometric Poisson distribution, different modifications of log-series distributions, and the Polya distribution (e.g., Wilks 1999; Anagnostopoulou et al. 2003; Deni et al. 2008; Deni and Jemain 2009). Deni et al. (2010) investigated the applicability of as many as 15 discrete distributions for the approximation of wet and dry spell durations over the Malaysian peninsula and found that five discrete distributions compete with each other in their skill to approximate WP and DP durations according to the Kolmogorov–Smirnov test (K–S test). Application of the Akaike Information Criteria (AIC) (Akaike 1974) has shown that these distributions were equally effective for the description of the WP and DP durations.

1) TRUNCATED GEOMETRIC DISTRIBUTION

In this work we apply the truncated geometric distribution (TGD). Although it was not explicitly tested in Deni et al. (2010), they found that similar distributions (e.g., the mixed geometric truncated Poisson distribution) successfully approximate WP and DP durations. Moreover, Deni et al. have shown that, generally, truncated distributions demonstrate better skills compared to their infinite analogs. In contrast to the standard geometric distribution,

\[ P(x_i = k) = p(1 - p)^{k-1}, \]  

where \( x_i \) (being an integer) is the duration of the continuous wet (dry) period in days and \( p = 1/d_s \), \( d_s \) is the mean duration (the distribution parameter), the TGD explicitly accounts for the number of wet/dry days in the record, implying virtually that the longest wet/dry spell can theoretically last no longer than the number of wet
or dry days considered. The probability density function of the TGD is given by

\[ P_t(x_t = k) = C p_t (1 - p_t)^{k-1}, \quad (2) \]

where \( p_t \) is the distribution parameter and the multiplier \( C \) accounts for the number of wet/dry days \( N \),

\[ C = \frac{1}{\sum_{k=1}^{N} p_t (1 - p_t)^{k-1}} = \frac{1 - (1 - p_t)^N}{1 - (1 - p_t)^N}, \quad (3) \]

leading to

\[ P_t(x_t = k) = \frac{1}{1 - (1 - p_t)^N} p_t (1 - p_t)^{k-1}. \quad (4) \]

The TGD is thus defined in the interval \([1, N]\), while the standard geometric distribution is defined in the interval \([1, \infty)\). The maximum likelihood estimators for \( p_t \), as well as an optimal iterative scheme for solving the estimator equation, are presented in appendix A. With Eqs. (4), (A3), and (A4), we can derive the PDF of the TGD and estimate percentiles related to a given duration. When estimating WP or DP durations for a given percentile we need to use the truncated integer of the resulting value (i.e., the number of whole days in the duration) to keep the discrete character of the TGD (this also applies to a standard geometric distribution).

For large \( N \) and small \( k \) the TGD approaches a standard geometric distribution with \( p_t \approx p \). But, both can be quite different for moderate and small \( N \) or relatively large \( k \).

Figure 2 shows the empirical histograms of wet and dry period durations and the approximation of these histograms by the TGD for several European locations for selected years. The histograms were computed from annual time series. Estimates of goodness of fit of TGD using a \( \chi^2 \) test are nearly everywhere above 95% and in 35%-40% of locations exceed 99%, being somewhat higher for the distributions of WPs compared to DPs. Application of the more powerful K–S test used also by Deni et al. (2010) gives somewhat lower (compared to the \( \chi^2 \) test) estimates of goodness of fit, confirming, however, the accurate approximation of empirical distributions by TGD. We have to note that the K–S test—typically applicable to continuous distributions—can be used for the discrete distribution (TGD) in its extended form (e.g., Conover 1972) only for locations where the number of WPs and DPs is large enough and the TGD can be approximated by the continuous one. We tested the competitiveness of the TGD with respect to the standard geometric distribution by analyzing the minimum AIC value for the two distributions and found that the TGD is always more effective than its infinite analog. Since we focus on the trends in the TGD parameters, the TGD distribution was fitted to the data and the goodness of fit analyzed for every individual year (season) to guarantee that the data are independent and identically distributed. Histograms and their approximations by the TGD (Fig. 2) imply that practically for all regions, except western Scandinavia, the distribution of the DP duration has a heavier tail than for the WP durations. This behavior reflects the higher occurrence frequency of short WPs compared to short DPs and the higher probability of long DPs compared to long WPs. The highest probability of 1-day WPs (>60%) is observed in southern Russia and the Ukraine with the probability of long WPs (>6 days) here being less than 1%. In western Scandinavia and the Netherlands the occurrence of 1-day WPs drops to 30%–40%, while the probability of occurrence for long WPs (e.g., more than 6 days) increases to 10%–12%. For the southern European region the occurrence of prolonged DPs is relatively large, even for durations longer than 15 days, while the probability of short DPs (about 20%) is only half of the value obtained for Norway or the Netherlands. We will show below the results for individual seasons. Plots for both seasons similar to those in Fig. 2 (no figures shown) imply the same behavior with seasonal differences, which will be discussed in sections 4 and 5.

2) FRACTIONAL TRUNCATED GEOMETRIC DISTRIBUTION

When considering changes in the duration of WPs and DPs, it is important to account for the relative contribution of WPs and DPs of a specific length to the total number of wet and dry days. This may help to eliminate the impact of changing numbers of wet and dry days from year to year. This impact is not trivial. For instance, Zolina et al. (2010) analyzed this problem using a Monte Carlo simulation of changes in wet day occurrence and argued that a growing number of wet days may contribute to both lengthening and shortening of the mean WP duration. To derive a theoretical distribution of the fractional contribution of WPs or DPs with a given length to the total number of wet (dry) days, we first derived the distribution of the fractional part of a random period \( k \) to the total number of days provided by \( n \) geometrically distributed random periods [see appendix B, Eq. (B4)] and then obtained an equation for the distribution of the relative contribution of periods...
with duration $k$ (in days) to the total number of wet days:

$$P_F(k) = C_F \frac{k}{n} p_i (1 - p_i)^{k-1},$$

where $C_F$ is linked to $C$ via

$$C_F = \frac{C p_i^n}{1 - (1 - p_i)^{n+1} - (n+1)(1 - p_i)^{n+1} p_i},$$

with $n$ the number of wet/dry periods in the record. We will name this distribution fractional TGD (FTGD). Since the FTGD is defined on the interval $[0, N]$ as the TGD, it is obvious that $\sum_{k=1}^{n} P_F(k) = 1$. Mathematical details of the derivation of the FTGD are given in appendix B.

Figure 3 shows, for the same regions as in Fig. 2, the distributions of the fractional contribution of wet/dry periods of a given duration to the total number of wet/dry days derived from the raw data and approximated by the FTGD. Typically, the FTGD is characterized by modal values of durations $>1$ day. In Scandinavia and northern continental Europe WPs with 3–4-day durations provide the largest contribution to the total number of wet days, and in southern Russia only the largest contribution comes from 1-day WPs. For the DPs the largest contribution to the total number of dry days in

![Image of Figure 2](image-url)
southern Russia comes from 4–6-day DPs, while the FTGD for Scandinavia and northern Europe peaks at 2–3 days. As for the TGD, the goodness of fit for the FTGD was tested via the $x^2$ test. For more than 95% of the locations these distributions fit the empirical distributions at the 95% significance level.

b. Methods for the analysis of interannual variability

We will analyze linear trends in the statistics of the durations of wet and dry spells. Linear trends were computed using least squares and linear trend significance was estimated using the Student’s $t$ test. As an alternative we also used the nonparametric Mann–Kendall test (Mann 1945; Kendall 1970), whose power was found in most cases to be similar or smaller compared to the Student’s $t$ test. Thus, all significance estimates in this study are based on the Student’s $t$ test. For some cases trend estimates were additionally analyzed with respect to the Hayashi (1982) reliability ratio ($R$), which represents an analog to signal-to-noise statistics (Buishand et al. 1988) and considers the confidence intervals of the statistical significance of trends. For trend estimates we considered the results to be significant at the 95% level (if not stated otherwise) if they satisfied both the Student’s $t$ test and Hayashi reliability ratio. Further details of the trend significance estimation can be found in Zolina et al. (2008).

For the analysis of simultaneous tendencies in the durations of WPs and DPs for the five regions with homogeneous sampling, we estimated the field significance
Field significance quantifies the required number of passes of single tests necessary to satisfy the overall significance for the area at a given level. Field or group significance was estimated according to Livezey and Chen from the binominal distribution and was also tested using the Walker test (Wilks 2006). These estimates should be carefully interpreted in densely sampled areas, like the Netherlands or Norway, where spatial correlation between the data records can be quite high, implying interdependency of time series. In this respect, the estimation of the rate of family-wise type I error (the probability of at least one conclusion that two samples originating from the same population differ) using the Walker test [being analogous to the Bonferroni–Sidak adjustment of individual significance tests, Keppel and Wickens (2004)] is one, but not necessarily the only possible way, demanding great scrutiny. For areas of high spatial correlation between the records this may result in a considerable decrease of the $p$ value. The problem of applying the Bonferroni–Sidak adjustment to serially correlated data was discussed by Zolina et al. (2008) for the DWD precipitation network and for similar cases in medical statistics by, for example, Perneger (1998) and Morgan (2007).

4. Climatology of wet and dry period statistics over Europe

To provide a reference for the variability of wet and dry spell durations over Europe, we show first the seasonal climatologies of the duration statistics for wet and dry periods. Figure 4 shows the climatological distributions of the mean duration of wet and dry periods for the cold and warm halves of the year over Europe. Since these estimates were obtained from the TGD and not from the actual data, according to Eq. (A3) the estimate of the mean duration also requires an estimate of $p_t$, which in the case of large $N$ is close to the inverse mean duration (as for a standard geometric distribution).

During the cold period the mean duration of WPs increases from 1.5 days over southern Russia and the Ukraine to more than 5 days over the Scandinavian Atlantic coast. During the warm period the mean duration of WPs is shorter compared to the cold season and varies from 1–1.5 to nearly 4 days holding the same spatial pattern as in the warm season. The mean
duration of DPs increases from 2–3 days in limited regions of Scandinavia and northern Europe to more than 10–12 days in southern Europe. The longest mean DPs of more than 10 days in winter and more than 16 days in summer are observed over the eastern Iberian Peninsula, the eastern Mediterranean, and southern European Russia. Locally, somewhat longer WPs and shorter DPs are observed in the Alpine region in both seasons.

In Fig. 5 we show the climatological distributions of TGD percentiles for very short (1 day) WPs and DPs and the duration of WPs and DPs corresponding to the 95th percentile of the TGD. The TGD percentile for 1-day duration quantifies the occurrence of WPs and DPs lasting one isolated day. Durations corresponding to the 95th percentile show the minimum length of the upper 5% of all WPs or DPs. The highest occurrence of 1-day WPs of more than 60% is observed in southern Europe and eastern European Russia with higher probabilities in the warm season. In central western Europe the occurrence of 1-day WPs varies from 30%–45% in winter to 40%–50% in summer. The lowest occurrences of very short WPs are observed along the Scandinavian Atlantic coast; values are typically less than 20% in the cold season and range from 20% to 40% in the warm season. The occurrence of 1-day DPs is considerably smaller compared to 1-day WPs. The highest probability of 1-day DPs is observed in northern Europe and Scandinavia (40%–45% in the cold season and 30%–40% in the warm season); the probability decreases to 10%–20% in southern Europe where no-rain periods typically last longer than one day, especially in the warm season. Occurrences of extremely long wet and dry spells are quantified in Figs. 5e–h by the durations corresponding to the 95th percentile of TGD. Over the Scandinavian Atlantic coast, the upper 5% of WPs last longer than 12 days in the cold season and longer than 9–10 days in the warm season. In central western Europe, the 95th percentile of the WP durations decreases to 5–7 days and becomes shorter than 3–4 days in southern Europe and eastern European Russia. In these regions the upper 5% of DPs have durations of more than 12 days (Figs. 5f,h). In northern Europe the value of the 95th percentile of DP durations decreases to 4–6 days in the cold season and to 6–8 days in the warm season. For practical applications sometimes, estimates of mean durations of WPs and DPs as well as estimates of the 95th percentile derived from the empirical data and not from the TGD might be important. Figure 6 shows differences in the durations of WPs corresponding to the 95th percentile derived from the empirical data and from the TGD. Differences are quite small and for most locations lie within ±5% of the actual durations. The largest differences may amount to ±10%. Similar results were obtained for DP durations (no figure shown). Interestingly, estimates derived from empirical data tend to be slightly higher compared to those revealed by TGD for relatively large durations and to be somewhat smaller for relatively short durations. Nevertheless, the estimate of high percentiles of WP and DP durations from empirical data seriously suffers from limited statistics, resulting in a low accuracy of estimation, and should be avoided. Differences in the mean durations lie within ±1% (no figure shown).

Estimates for higher percentiles corresponding, for example, to 50-yr return values are important for quantifying the longest possible periods of continuous precipitation or extremely long droughts. However, such estimates should be based on area-averaged time series, which can only be successfully provided for the Netherlands and southern Norway where the sampling density is sufficiently high. For the Netherlands area-averaged estimates of 50-yr return values for WPs result in 19 ± 7 days in winter and 16 ± 7 days in summer, and estimates for the duration of DPs are 21 ± 4 days and 22 ± 3 days in winter and summer, respectively. For Scandinavia 50-yr returns in the duration of WPs equal 16 ± 1 days in winter and 13 ± 2 days in summer. Estimates of the Scandinavian DPs lead to 18 ± 2 days and 22 ± 2 days in winter and summer, respectively. Note that similar estimates for individual stations may seriously deviate from the ones given above; however, they should not be discussed seriously because the accuracy of these estimates is very low.

Also of interest is the contribution of extremely long wet and dry periods to the total number of wet and dry days, which can be derived from FTGD. Applying Eqs. (5) and (6) and the formalism described in appendix B, we computed durations corresponding to different percentiles of the FTGD. Figure 7 shows estimates of durations corresponding to the 95th percentile of the FTGD, or in other words, the length of wet and dry spells contributing 95% of all wet and dry days per season, respectively.

Although the patterns in Figs. 5e–h and Fig. 7 are qualitatively comparable, they exhibit significant quantitative differences related to the shape of the FTGD (Fig. 3) and the actual number of wet/dry days. Thus, during the cold season over Scandinavia and the northern United Kingdom 95% of the wet days are formed by wet spells of up to 20 days in length with a maximum value of 22 days. Note that the 95th percentile of the TGD (Fig. 5e) returns for this region wet spells of 14 days. Over the Netherlands and northern continental Europe 95% of the wet days are formed by spells of up to 9 days in the cold season and up to 8 days in the warm
FIG. 5. Distribution of the percentiles of the TGD corresponding for the (left) cold and (right) warm seasons to very short (1 day) (a),(b) WPs and (c),(d) DPs as well as the actual duration (days) of (e),(g) WPs and (f),(h) DPs corresponding to the 95th percentile of the TGD for (left) October–March and (right) April–September.
season. In northern Europe 95% of the dry days are due to DPs of up to 9 days in length in the cold season and 10–12 days in the warm season, while in southern Europe this value increases to more than 20 days in most regions.

5. Changes in the durations of wet and dry periods during the last 60 years

In the following we present the analysis of the long-term evolution of linear trends in the duration of
European WPs and DPs for the two seasons. Figure 8 shows linear trends in the mean duration of WPs and DPs for the period from 1950 to 2009. During the cold season the mean duration of WPs increases over most of northern and central Europe with the strongest trends of more than 6% decade\(^{-1}\) identified along the Scandinavian Atlantic coast and in northern European Russia. This implies a lengthening of WPs from 1 to more than 2 days during the last 60 years. Statistically significant negative trends in the duration of WPs are found in southern Europe, with the strongest shortening of WPs over the Iberian Peninsula (0.7 days during the 60-yr period). Warm season trends in the duration of WPs show a tendency similar to the cold season trends in central western and northern eastern Europe (growing duration of WPs by 3%–4% decade\(^{-1}\)). At the same time, over Scandinavia and northwestern Russia warm season trends in the duration of WPs are opposite to those for the cold season, clearly implying a regional seasonality in long-term changes with growing tendencies in the cold season and downward changes in the warm season. Also, in southern Europe warm season trends in the duration of WPs are primarily weakly positive, contrasting clearly negative cold season trends.

For the duration of dry spells (Figs. 8c,d) trend patterns are quite consistent in the cold and warm season over central and northern Europe: DPs are becoming shorter in Scandinavia and northern France by 6%–8% decade\(^{-1}\) (more than 2 days) and longer in central western Europe and over northern European Russia where DPs became longer by 1.5 to more than 2.5 days during the last 60 years. At the same time, in southern Europe trend patterns for the duration of DPs show a clear seasonality with growing duration for DPs in the cold season and statistically significant shortening in the warm season.

The patterns of linear trends in the occurrences of very long wet and dry spells quantified by the 95th percentiles of the TGD (Fig. 9) largely replicate those for the mean durations (Fig. 8) and imply two remarkable phenomena in the long-term tendencies of the duration of extreme European WPs and DPs. First, Fig. 9 identifies the regions with a clear seasonality of trends in the duration of WPs and DPs. Over the Scandinavian Atlantic coast extremely long wet spells become longer during the cold season by 5%–7% decade\(^{-1}\) (2–2.5 days
since 1950) and shorter during the warm season by 2%–4% decade$^{-1}$ (1.5–2 days since 1950). For the longest dry spells (Figs. 9c,d) a seasonality pattern is evident in southern central and eastern Europe with increasing duration of prolonged DPs in the cold season (4%–8% decade$^{-1}$) and shortening in the warm season. Weaker signatures of seasonality are also found for the WPs in northwestern Russia and for the DPs over northern Germany and the Iberian Peninsula. Over other regions the 60-yr tendencies in the duration of extremely long spells are consistent during both cold and warm seasons. A growing occurrence of the longest WPs throughout the year is identified in western central Europe and northeastern European Russia. A statistically significant shortening of extremely long DPs during both seasons is observed over western Scandinavia and France. A pattern of strongly growing occurrences of extremely long DPs in both seasons is clearly evident over almost all of eastern Europe.

To identify the regions where a lengthening of wet spells is associated with decreasing durations of prolonged dry episodes (Figs. 9a,c). At the same time, over central and northern European Russia, cold season durations of both wet and dry spells have increased during the last 60 years. A similar tendency is observed in the limited area of the Netherlands. For the cold season (Figs. 8b,d; 9b,d) marked tendencies during the last 60 years were obtained for the two small well-sampled areas—a simultaneous shortening of both WPs and DPs over Scandinavia and an increase (by about 2%–4% and 4%–7% decade$^{-1}$ for WPs and DPs, respectively) over the Netherlands. A tendency similar to that for the Netherlands is evident in northern France and northern Germany as well as in some regions of central and southern European Russia.

Second, the distribution of linear trends (Figs. 8, 9) clearly identifies regions of opposite and parallel tendencies in the durations of mean and extremely long WPs and DPs. During the cold season over Scandinavia the increasing duration of mean and extremely long wet spells is clearly associated with decreasing durations of prolonged dry episodes (Figs. 9a,c). At the same time, over central and northern European Russia, cold season durations of both wet and dry spells have increased during the last 60 years. A similar tendency is observed in the limited area of the Netherlands. For the cold season (Figs. 8b,d; 9b,d) marked tendencies during the last 60 years were obtained for the two small well-sampled areas—a simultaneous shortening of both WPs and DPs over Scandinavia and an increase (by about 2%–4% and 4%–7% decade$^{-1}$ for WPs and DPs, respectively) over the Netherlands. A tendency similar to that for the Netherlands is evident in northern France and northern Germany as well as in some regions of central and southern European Russia.

To identify the regions where a lengthening of wet spells is associated with parallel or opposing tendencies for dry spells, we show in Fig. 10 the locations for which linear trends in the mean duration of WPs and DPs are parallel with different statistical significance. For both cold and the warm seasons Fig. 10a clearly identifies regions with parallel positive trends; that is, both WPs and DPs become longer. These are the densely sampled, although small, area of the Netherlands and a large
region of eastern Europe with moderate sampling. In the warm season (Fig. 10b) this tendency is also pronounced over the Netherlands and, to a lesser extent, over eastern Europe. Simultaneous shortening of the wet and dry spells is observed over southern Norway with a more pronounced pattern in the warm season (Fig. 10b). Similar estimates found for the higher percentiles of the durations of WPs and DPs also result in regionally robust patterns.

As explained in section 4, time variability in the return values of the durations of WPs and DPs can be accurately quantified only for the regions with high sampling, which allow for spatial averaging. Figures 11a,b show time series of 20-yr return values in the duration of wet and dry spells for different regions for the cold season. Return values were computed for every year from the percentiles of the TGD using the actual number of WPs and DPs over all stations within the region. In this sense, Fig. 11 shows how the return values change during the 60-yr period. Such considerations are important for practical applications when risk management actions are planned using estimates based on data for limited periods. Over the Netherlands, both extremely long wet and dry spells increased strongly over the past six decades: in October–March spatially averaged 20-yr return values of the duration of WPs increased by about 3 days. Simultaneously, the 20-yr return values of DPs increased by 4 days. Similar estimates for 50-yr return values (no figure shown) give increases of 4 and 5 days, respectively.

Figure 12 identifies western European locations with consistently opposite trend signs for the duration of WPs and DPs. In the cold season there is a clear tendency for lengthening of WPs going along with a simultaneous shortening of DPs over southern Scandinavia and northern France. Shorter WPs go hand in hand with longer DPs over the Balkan States, Romania, and Bulgaria. During the warm season (Fig. 12b), a pattern of opposite trends (longer WPs and shorter DPs) holds over France only. Figures 11c,d give an example of opposite tendencies for durations of extremely long WPs and DPs in Scandinavia. Over the Scandinavian Atlantic coast in the cold season, 20-yr return values of WPs increase by more than 3 days, while extreme DPs decrease by nearly 4 days; corresponding estimated tendencies in 50-yr return values are 20%–30% stronger.

Table 1 presents the results of estimating field significance of the patterns holding the same trend sign and of the patterns holding opposite trend signs for the four regions with relatively homogeneous sampling. Their selection was justified in section 2b. Over the Netherlands and eastern Europe, wet and dry periods exhibit a parallel increase in length during both seasons. Field significance computed according to Livezey and Chen (1983) from the binominal distribution is always above 95%, and amounts to 99% for both regions in the cold season and for the Netherlands in the warm season. The Walker test (Wilks 2006) implies a field significance at the 95% level. Over Norway during the cold season there is a clear pattern of lengthening of WPs with simultaneous decreases in the duration of DPs, while during the warm season both WPs and DPs experienced shortening during the last decades. These patterns hold field significance at the 99% level according to the binominal distribution and at the 95% level according to a Walker test. As noted earlier (see section 3), results
FIG. 11. Time series of 20-yr return values of (a),(c) WPs and (b),(d) DPs over (a),(b) the Netherlands and (c),(d) the Scandinavian Atlantic coast for October–March period. Gray shading corresponds to the standard deviations of the estimates derived from the contributing stations.
for areas densely populated with rain gauges should be considered with some caution. The correlation between individual records within 80–100 km amounts to more than 0.8 in Norway, being even higher in the Netherlands. For Norway and the Netherlands this implies a lowering of the Bonferroni $p$ value to $0.025$. Patterns of opposite tendencies in the duration of WPs and DPs over France and central southern Europe also hold the field significance at the 99% level in the cold season and at least at the 95% level in summer.

6. Role of regrouping of wet days and changes of their number in the variability of wet and dry period durations in Europe

Changing durations of wet and dry periods can be caused either by a changing total number of wet (or dry) days or by a temporal regrouping of individual wet and dry days, or any combination of both. Figuratively speaking, changes in the duration of WPs and DPs are comparable to a redistribution of beads on a necklace with either a fixed or a changing total number of beads. Discriminating between effects is, however, not an easy task. Zolina et al. (2010), who considered wet spells only for annual time series, tested the impact of changes in the total number of wet days on the duration of WPs by simulating observed trends in the total number of wet days using bootstrapping. They concluded that the observed changes in the number of wet days can only explain four to nine times smaller trends in the duration of wet spells compared to the observed ones. Sensitivity experiments similar to those of Zolina et al. also show that the observed trends in the number of wet days cannot explain the changes in the duration of WPs and DPs. During the last 60 years the cold season number of wet days slightly increased by 1%–3% in Scandinavia and eastern Europe and decreased by 1%–2% in southwestern and central Europe. During the warm season the number of wet days increased by less than 2% in Scandinavia and decreased slightly in central Europe and the southern Ukraine. No statistically significant trends were found in southern Europe and European Russia. Note that these estimates account for the number of wet days with significant (e.g., exceeding 1 mm day$^{-1}$) precipitation and can be somewhat different from the tendencies in the total number of wet days including light precipitation events as, for example, analyzed in Zolina et al. (2008). The largest effect of a changing number of wet and dry days on the lengths of WPs and DPs is observed over Scandinavia in the cold season for which Figs. 6, 7, and 9 identify remarkable opposite tendencies in the duration of WPs and DPs. Here the growing number of wet days accounts for 50%–60% of the trends. In other regions this effect is typically below 20%. Moreover, the simultaneous lengthening of WPs and DPs in some regions indirectly evidences that these changes are due to the regrouping of wet days.

To provide more accurate estimates of the tendencies in WP and DP durations, we analyzed the fractional contribution of prolonged wet and dry episodes to the total number of wet and dry days using the FTGD equations (5) and (6); see appendix B. Figure 13 shows...
Table 1. Estimates of field significance (FS) from the binominal distribution and the significance of the Walker test (W) for the hypothesis that the durations of both WPs and DPs exhibit similar/different linear trends (lengthening or shortening) for different regions. WP+ DP+ and WP− DP− correspond to the simultaneous lengthening and shortening of WPs and DPs, respectively. WP+ DP− (WP− DP+) indicates lengthening (shortening) of WPs going along with shortening (lengthening) of DPs.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Season</th>
<th>Norway</th>
<th>The Netherlands</th>
<th>France</th>
<th>Central Southern Europe</th>
<th>Eastern Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean duration of WPs and DPs</td>
<td>Oct–Mar</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP+ DP+ FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
</tr>
<tr>
<td></td>
<td>Apr–Sep</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP+ FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
</tr>
<tr>
<td>90th percentile of the duration of WPs and DPs computed from the TGD</td>
<td>Oct–Mar</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP+ DP+ FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
</tr>
<tr>
<td></td>
<td>Apr–Sep</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP+ FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
</tr>
<tr>
<td>90% fractional contribution of WPs and DPs to the total number of wet (dry) days computed from the FTGD</td>
<td>Oct–Mar</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP+ DP+ FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
</tr>
<tr>
<td></td>
<td>Apr–Sep</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP+ FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
<td>WP− DP− FS⁹ W⁹</td>
<td>WP+ DP− FS⁹ W⁹</td>
</tr>
</tbody>
</table>

⁹ Significant at 99% level.
⁸ Significant at 95% level.
⁷ Significant at 90% level.

The smoothed temporal evolution (5-yr running mean) of the normalized occurrence anomalies $P'(x)$ for WP and DP contributions to the total number of wet/dry days for the Netherlands, southern Norway, and eastern European Russia. The anomaly $P'(x)$ is computed via

$$P'(x) = \frac{P(x) - \bar{P}(x)}{\sigma[P(x)]}$$  (7)

in which $x$ is the duration of WPs or DPs, $P(x)$ the probability of occurrence of spells of this duration for an individual year, $\sigma[P(x)]$ the standard deviation of the probability distribution for a particular duration $x$, and the overbar is the averaging operator. The Netherlands and eastern European Russia experienced an increased occurrence of prolonged WPs and DPs during the last 60 years while occurrences of short episodes became less frequent. Especially during the period from the 1980s to the 2000s long wet and dry spells occurred more frequently. Opposite tendencies (increasing occurrence of short spells and declining number of prolonged spells) are observed for southern Norway. In addition, from 1980 onward we observe positive occurrence anomalies for both extremely long (short) WPs (DPs).

Using the FTGD [Eqs. (5) and (6)] we computed the upper threshold of WP and DP durations, which encompass 90% of the total number of wet or dry days, respectively. Figure 14 shows the locations for which the linear trends of these thresholds hold the same sign for WPs and DPs (similar to Fig. 8 for the durations of spells). The patterns in Fig. 14 are quite close to those found in Figs. 8 and 10, which shows that the elimination of the effect of a changing number of wet days does not affect the results, thus implying the changing character of precipitation. During both cold and warm seasons wet and dry spells tend to increase over the Netherlands and eastern Europe. In the warm season WPs and DPs shrink in length over Scandinavia and southern Europe. Opposing tendencies in the length of WPs and DPs contributing 90% of wet and dry days, respectively, are observed over France (growing contribution from WPs and decreasing contribution from DPs during both seasons) and over central southeastern Europe (shortening of WPs and lengthening of DP in the cold season with the opposite tendencies in the warm season), which again is consistent with Fig. 12.
7. Summary

We analyzed the seasonal (cold and warm halves of the year) variability of the duration of wet and dry periods over Europe using rain gauge observations for the period from 1950 to 2009. To obtain robust statistics the probability distributions for the durations were approximated by the TGD and by a new FTGD addressing the fractional contribution of WPs and DPs of different durations to the total number of wet and dry days. The linear trends in the WP and DP durations differ regionally and by season. In the cold season (October–March) WP durations increased from 2% to 7% decade$^{-1}$ over northern and central Europe and tended to slightly shrink in southern Europe. During April–September (warm period) WP durations over Scandinavia and some parts of eastern Europe shortened significantly. Very long WPs and DPs may exhibit changes of 3–5 days over the last decades.

Trends in DP durations are not always and everywhere opposite to trends in WP duration. Over the Netherlands and eastern Europe both WPs and DPs extend in length, especially in the cold season, suggesting a regrouping of the wet days into more prolonged wet episodes and dry days into more prolonged dry episodes. A simultaneous shortening of WPs and DPs is observed over southern Scandinavia in the warm season. Over France and central southern Europe during both halves of the year—and over the Scandinavian Atlantic coast only in the warm season—tendencies in durations of wet and dry periods have opposite signs. Such tendencies imply that a lengthening of WPs occurs at the expense of DPs or vice versa. These regional patterns of coordinated changes in the mean durations of wet and dry periods as well as in the higher percentiles are confirmed by field significance tests. Long-term tendencies in the fractional contribution of wet and dry spells to the total number of wet days are consistent with those implied by the analysis of mean and extreme durations. This proves that the observed trends are primarily due to a rearrangement of wet and dry days rather than changing numbers of wet days.

Our continental-scale results confirm and extend some earlier regional findings about changes in the duration of wet and dry periods, such as the lengthening of WPs over the Swiss Alps (Schmidli and Frei 2005) and the increase in length of prolonged dry episodes in the Mediterranean (Kuglitsch et al. 2010) and over northern Italy (Todeschini 2012). We also identified a strong seasonality in the trends of WP durations, especially in Scandinavia and in southern western Europe. Thus we can conclude that the overall increase of WPs in Scandinavia and the decrease of WPs in the Mediterranean region indicated by Zolina et al. (2010) are largely due to changes during the cold season.

Fig. 13. Five-year running means of the normalized occurrence anomalies of the contribution of (a),(c),(e) WPs to the total number of wet days and (b),(d),(f) DPs to the total number of dry days derived for (left) the Netherlands, (middle) European Russia, and (right) southern Scandinavia.
8. Discussion

A pancontinental analysis of the durations of wet and dry periods requires special attention to the data coverage and completeness of individual records. In this respect, the interpretation of our results suffers from the very inhomogeneous spatial data coverage in Europe. Most reliable results can only be obtained if dense precipitation networks are used; thus, in this respect, our findings are most robust for the Netherlands and Norway; reliable for Germany, France, European Russia, and the Ukraine; and should practically be ignored for the almost unsampled (in the ECA collection) areas of the United Kingdom, Poland, Czech Republic, Slovakia, Bulgaria, Hungary, and some other states. All of these countries have their national collections (see, e.g., Kveton and Zak 2008; Kysely 2008; Maran et al. 2010a; Łupikasza et al. 2011; Herrera et al. 2012; and many others); however, these collections are not shared with the international community, restricting international studies for these countries to subpar analyses and making it difficult to accurately estimate continent-scale climate changes, which may affect the well-being of these same nations. This issue has been widely discussed at different workshops and conferences, however, the achieved progress is still insufficient.

The simultaneous lengthening or shortening of WPs and DPs over all regions hints at structural changes in European precipitation. Although we considered here changes in the durations of WPs and DPs separately, these tendencies are likely not independent. For a proper analysis of this phenomenon, statistical estimation techniques based on the TGD or similar PDFs can be further extended to the joint distribution of WP and DP durations, implying the use of hypergeometric distributions and the analysis of transition probabilities in Markov chains. This approach was first implemented by Gabriel and Neumann (1962) and applications are given in Harrison and Waylen (2000), Ochola and Kerkides (2003), Srinivasa Reddy et al. (2008), Schoof and Pryor (2008), Subash et al. (2009), Khoshghalb et al. (2010), and others.
It is important to identify the mechanisms or climatic processes responsible for the observed changes in wet and dry period durations. Cold season increases in the mean WP duration and a growing occurrence of extremely long wet spells could be attributed to changing cyclone activity in the Atlantic–European sector. Some studies (e.g., Gulev et al. 2001; Trigo 2006; Wang et al. 2009; and others) found that the number of deep cyclones has an increasing tendency over Europe. However, to establish a direct link between cyclone activity and WP durations, the sole consideration of the number of cyclones may fall short. Prolonged wet periods are more likely linked to the occurrences of cyclone series (Mailier et al. 2006) or to particular regional airflow regimes (e.g., Marau et al. 2010a) that may, indeed, change the degree of intermittence of wet and dry days to a larger extent than just the number of cyclones. This is particularly important for understanding the strong cold season increase of WP durations over the Atlantic coast of Scandinavia. During the last few decades an enhanced poleward deflection of Atlantic storm tracks was observed in this region and this tendency is expected to become more pronounced in the future climate (Leckebusch and Ulbrich 2004; Loeptien et al. 2008). The signal of lengthening of wet spells over the Scandinavian Atlantic coast is not replicated in, for example, southern Sweden, most probably because of the strong impact of the local orography on the moisture transport, which implies different precipitation regimes to the east and to the west of the Scandinavian mountain ridge (Gustafsson et al. 2010). Finally, it is important to consider the impact of regional orography on the duration of WPs.

As in the case with wet spells, likely associated with clustering cyclones into series and specific airflow regimes, the attribution of dry spell changes requires an extensive analysis of blocking events (e.g., Lupo et al. 1997; Wiedenmann et al. 2002; Trigo et al. 2004; Croci-Maspoli et al. 2007b) based on advanced indices (e.g., Schalte et al. 2011). This phenomenon might provide a better connection with circulation patterns than the analysis of the North Atlantic Oscillation (NAO) index, whose variability may not necessarily capture the variability in DP statistics. López-Moreno and Vicente-Serrano (2008) found high spatial variability and strong seasonality in the responses of droughts to the NAO phases. A clear signal of dry period lengthening over European Russia in the cold season may be associated with changing blocking dynamics as identified by Croci-Maspoli et al. (2007a), Petoukhov and Semenov (2010), and Stillmann et al. (2011).

An extended analysis of the mechanisms for change in the duration of wet and dry episodes should also involve precipitation intensity during the WPs and temperature regimes during the DPs. This is particularly important for the analysis of impacts of extremely long wet and dry periods. Indeed, an extremely long WP with an average precipitation intensity of a few millimeters per day or a very long DP with an average temperature close to norm may not result in hazardous flooding or a heat/cold wave. Zolina et al. (2010) argued for stronger precipitation extremes occurring during longer wet periods over Europe. At the same time, Zhang et al. (2011) showed that in China a growing duration of WPs does not seriously affect the total amount of precipitation. An attempt to analyze frequency–duration–intensity relationships for model data was recently performed by Kao and Ganguly (2011). Further work may help to derive advanced hydroclimate indices involving precipitation duration in addition to the number of wet days (Giorghi et al. 2011). Our work also provides good prospects for the relations between precipitation duration and intensity. The detection of WPs can be useful for the analysis of precipitation extremes associated with particular spells and might be an alternative to the consideration of block maxima, which are widely used for the analysis of extreme precipitation (Marau et al. 2010b; Friederichs 2010).

A direct association of WP durations with the intensity of floods is complicated due to the nonlocal character of the impact of precipitation on flooding (e.g., Ashagrie et al. 2006). For instance, Gaume et al. (2009) found reductions of discharge in southern France and northern Italy during the last six decades of up to 100%, which is consistent with the shortening of WPs and lengthening of DPs as demonstrated by our study. Mudelsee et al. (2003, 2004) show that trends in flood frequency in Europe are not pronounced during the last decades, however Bunde et al. (2005) argued that there was an intensified clustering of floods during this period, which can reflect—besides human influence on the characteristics of river basins—a clustering of precipitation into prolonged spells. Further efforts to study the association of flooding with WP durations involving an analysis of groundwater recharge and soil moisture storage in addition to precipitation intensity (e.g., Maxwell and Kollet 2008) can shed more light on the linkages between the dynamics of wet spells and hydrological hazards, such as disastrous landslides (e.g., Marques et al. 2008; Klimes et al. 2009; Barredo 2009).

Our analysis might also be a very effective approach for an extended evaluation of precipitation in reanalyses and climate model simulations. Precipitation in reanalyses is one of the most uncertain parameters owing to the persistently poor accuracy of parameterized
convective processes. Zolina et al. (2004) showed that the interannual dynamics of precipitation in reanalyses over Europe may largely disagree with the dynamics revealed by station data, primarily because of the effect of light precipitation in reanalyses. Analysis of the durations of WPs and DPs in reanalyses can add another dimension to their intercomparison and validation against in situ observations. Similar analyses performed for climate model simulations may help to identify the mechanisms driving changes in precipitation regimes in an anthropogenically forced climate simulated by models (Russo and Sterl 2012). Lenderink and van Meijgaard (2008) showed in high-resolution model simulations that the intensity of short-term precipitation events may increase at a pace exceeding that implied by the Clausius–Clapeyron relationship (e.g., Trenberth et al. 2003; Allan and Soden 2008). The accurate quantification of WPs and DPs in the future climate will help to identify time scales of precipitation of different intensities and, thus, provide more information on the changing character of precipitation. This is especially important for Europe, where the role of climate change and natural variability in changing precipitation extremes is hardly discernible, especially outside of northern Europe (Kendon et al. 2008).

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APPENDIX A

Maximum Likelihood Estimator for the Parameter of the Truncated Geometric Distribution (TGD)

In contrast to a standard geometric distribution equation (1) for which the distribution parameter is inversely proportional to the sample mean \( p = 1/\bar{X} \), the parameter estimator for TGD is somewhat more complicated. Let the random variable \( X \) be distributed according to the TGD

\[
P(X = k) = Cp_qk^{q-1},
\]

where \( k \) is an integer, \( 1 \leq k \leq N \), \( p_i \) is the unknown distribution parameter of the TGD, \( N \) is the known number of wet/dry days in the record, and \( q = 1 - p \). The equality

\[
\sum_{k=1}^{N} P(X = k) = 1
\]

implies

\[
C = (1 - q)(1 - q)^{-N}p_{t}^{-1}.
\]

To estimate the unknown parameter \( p_i \) for a sample \( X_1, \ldots, X_n \), where all \( X_1, \ldots, X_n \) are independent and identically distributed according to (A1) random variables, we can derive the following maximum likelihood function:

\[
L(p; X_i) = \sum_{i=1}^{n} [\ln C + \ln p_i + (X_i - 1) \ln q]
\]

\[
= N(\ln C + \ln p_i) + \left( \sum_{i=1}^{n} X_i - N \right) \ln q.
\]

Taking the derivative with respect to the argument \( p_i \) and satisfying the condition \( \delta L/\delta p_i = 0 \), we get the equation

\[
\frac{1}{p} - \frac{N(1 - p_i)^{N-1}}{1 - (1 - p_i)^{N}} + \frac{1}{1 - p_i} = \bar{X},
\]

where \( \bar{X} \) is an average over the sample (i.e., \( \bar{X} = N^{-1} \sum_{i=1}^{n} X_i \)). An estimator similar to (A5) for a less general case, however, was derived by Thomasson and Kapadia (1968). Equation (A5) can be solved numerically using

\[
\frac{1}{p_i^{N-1}} - \frac{N(1 - p_i)^{N-1}}{1 - (1 - p_i)^{N}} + \frac{1}{1 - p_i} = \bar{X},
\]

where \( p_i \) denotes the \( p \) value in the \( l \)th iteration, starting from the known initial iteration \( p^0 \). It is easy to prove that there is only one root of Eq. (A5) in the interval \([0, 1]\).

APPENDIX B

Derivation of the Fractional Truncated Geometric Distribution (FTGD)

We first derive the distribution of the fractional part of one random sample \( X_i = k \) in the sum of \( n \) random samples distributed according to the TGD (A1):

\[
\text{APPENDIX B}
\]

\[
\text{Derivation of the Fractional Truncated Geometric Distribution (FTGD)}
\]

We first derive the distribution of the fractional part of one random sample \( X_i = k \) in the sum of \( n \) random samples distributed according to the TGD (A1):
where \( X_1, \ldots, X_n \) are independent and identically distributed integer random variables (durations) with the distribution (A1), \( k \) is the duration of a single wet/dry event, and \( n \) a known integer. Applying the full probability formula, we get

\[
F(y) = P\left( \frac{X}{\sum_{i=1}^{n} X_i} = y \right), \tag{B1}
\]

where \( X_i, \ldots, X_n \) are independent and identically distributed integer random variables (durations) with the distribution \((A1)\), \( k \) is the duration of a single wet/dry event, and \( n \) a known integer. Applying the full probability formula, we get

\[
F(y) = \sum_{k=1}^{\infty} pq^{k-1} P\left( \sum_{i=1}^{n-1} X_i = \frac{k}{y} \right)
= \sum_{k=1}^{\infty} pq^{k-1} P\left( \sum_{i=1}^{n-1} X_i = \frac{k}{y} - k \right). \tag{B2}
\]

Since the sum of the geometric random variables in (B2) is distributed according to the negative binomial distribution (Spiegel 1992 p. 118), Eq. (B2) can be rewritten as

\[
F(y) = \sum_{k=1}^{\infty} pq^{k-1} P\left( \sum_{i=1}^{n-1} X_i = \frac{k}{y} - k \right)
= \sum_{k=1}^{\infty} \left( \frac{n - 2 + u}{u} \right) p^n q^{u+k-1}, \tag{B3}
\]

where \( u = k(y^{-1} - 1). \) It is important to note that the binomial coefficients in (B3) make sense only for integer \( u \). Thus, the sum (B3) accounts only for integers \( u \) under \( k \geq 1 \), otherwise the corresponding terms vanish. Computationally, (B3) may lead to a very small loss of the cumulative probability, especially for the cases when the number of wet/dry days is small; however, this can be minimized by statistical optimization of the solution. Equation (B3) gives the distribution of the fractional part of one random sample in the sum of \( n \) random samples and allows for the estimation of the probability of occurrence of wet/dry periods providing a given contribution to the sum of wet days.

Now we can easily derive the distribution of the fraction of the sum of all geometric random variables (wet/dry spells with duration \( k \)) to the total number of wet/dry days,

\[
F(k) = P(y = k), \quad Y = \frac{X}{n}. \tag{B4}
\]

The conditional probability of the contribution of one wet/dry period with duration \( k \) obviously equals

\[
F_1(k) = P\left( \frac{X}{n} X = k \right) = \frac{k}{n}, \tag{B5}
\]

where \( n \) is the total amount of wet/dry days. Therefore, the nonconditional probability according to the full probability formula will be given by

\[
P_F(k) = C_F^{-1} p_t^{(k-1)} (1-p_t)^{n-1}, \tag{B6}
\]

which is identical to (5). The condition

\[
\sum_{k=1}^{n} F_1(k) = 1
\]

immediately implies the formula for \( C_F \):

\[
C_F = \frac{C_F p_t}{1 - (1-p_t)(n+1)}, \tag{B7}
\]

which is identical to (6).

REFERENCES


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