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Changing structure of European precipitation: Longer wet periods leading to more abundant rainfalls

Olga Zolina,[1,2] Clemens Simmer,[1] Sergey K. Gulev,[2] and Stefan Kollet[1]

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[1] Analysis of the duration of wet spells (consequent days with significant precipitation) in Europe and associated precipitation is performed over the period 1950–2008 using daily rain gauge data. During the last 60 years wet periods have become longer over most of Europe by about 15–20%. The lengthening of wet periods was not caused by an increase of the total number of wet days. Becoming longer, wet periods in Europe are now characterized by more abundant precipitation. Heavy precipitation events during the last two decades have become much more frequently associated with longer wet spells and intensified in comparison with 1950s and 1960s. The changes in the distribution of temporal characteristics of precipitation towards longer events and higher intensities should have a significant impact on the terrestrial hydrologic cycle including subsurface hydrodynamics, surface runoff and European flooding.
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1. Introduction

[2] European daily rain gauge observations and reanalyzes show upward tendencies in mean and heavy precipitation over the last decades [*Klein Tank and Koennen*, 2003, hereafter referred to as KTK03; *Zolina et al.*, 2005; *Groisman et al.*, 2005] and an increase in fractional contribution of heavy rainfalls to precipitation totals by 3–4% per decade [KTK03; *Moberg et al.*, 2006; *Zolina et al.*, 2009]. These tendencies were confirmed by regional studies [*Frei and Schär*, 2001; *Zolina et al.*, 2008] and are consistent with the climate model projections [*Semenov and Bengtsson*, 2002; *Emori and Brown*, 2005; *Scaife et al.*, 2008].

[3] These analyses considered wet days (WD) by accounting for their daily sums while omitting the duration. However, the impact of precipitation on flooding is strongly related to the number of consecutive WDs with catastrophic floods being associated with anomalously long precipitation periods. Only few studies analyzing climate tendencies addressed precipitation duration. *Kunkel et al.* [1999, 2003] considered consecutive series of both dry and WDs and found differences in the interannual behavior of the intensity of heavy rainfalls for different rain durations over the US. *Schmidli and Frei* [2005] reported growing duration of wet spells over Swiss Alps during the 20th century. *Brommer et al.* [2007] found decreasing occurrence of the long-duration storms during 1948–2004 over the US, that agrees with *Groisman and Knight* [2008] reporting the increase of the duration and occurrence of dry day episodes over the conterminous US during the warm season.

[4] In this work we quantified changes in the duration of precipitation events during 1950–2008 using daily data from nearly 700 European rain gauges and associated changes in the intensities of mean and heavy precipitation with the duration of events. This allows us to analyse the alternation of wet periods with different durations and to quantify changes in the structure of heavy precipitation on synoptic scale, thus, providing new metrics of precipitation variability useful for hydroclimate applications.

2. Data and Pre-processing

[5] Daily rain gauge observations were taken from the recently updated European Climate Assessment (ECA) dataset. Details of the ECA composition are given by *Klok and Klein Tank* [2009]. Over European Russia, Belorussia and Ukraine for the 1990s and 2000s 57 ECA stations contain artifacts due to incorrect record decoding. These were substituted by the original data from the Russian Hydrometerological Service (RHS) collection and 32 new RHS stations were added. From the resulting 1558 stations we selected 699 records which miss less than 10% of daily values in the annual records. They cover the period 1950–2008 with the highest density in the Western Europe and Scandinavia.

[6] Besides the traditionally used in precipitation analysis WDs we introduce wet spells or wet periods (WPs). For each year WPs were quantified as consecutive days with significant precipitation (>1 mm/day). This threshold excludes very light precipitation and accounts for the limited accuracy of rain gauges [*KTK03*]. This threshold was used for identification of dry day spells [*Groisman and Knight* 2008]. For the WPs we analyzed their durations and associated intensities.

3. Results

[7] Climatological average probability of WP durations decreases exponentially with length (Figure 1a). Isolated WDs contribute about 50% to the total number of WPs. Regionally this fraction varies from 30–40% in Scandinavia and Western Europe to ≈60% in Southern Russia and Ukraine. The 90th percentile (10% of the longest WPs) ranges from 3 days in Southern Europe to about 7 days in Scandinavia. Fractional contribution of different WPs to the total number of WDs (Figure 1a) shows that daily and 2-day events account for ≈50% of all WDs. The remaining WDs contribute from 15–20% for 3-day events to <1% for 12-day WPs. The longest averaged WP duration of >3 days is found

[1]Meteorologisches Institut, Universitaet Bonn, Bonn, Germany.
[2]P. P. Shirshov Institute of Oceanology, Moscow, Russia.

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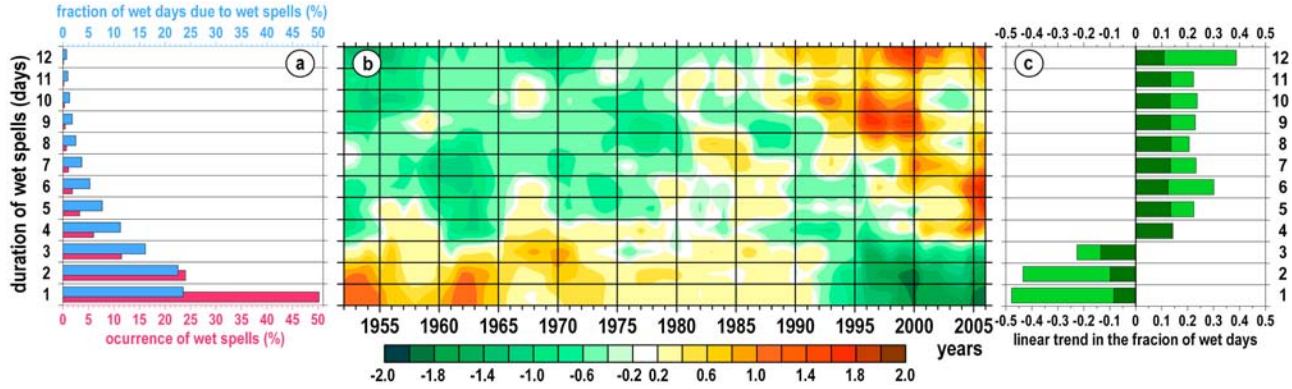

Figure 1. (a) Climatological distributions of the occurrence of WP durations (red) and of the fractional contribution of different WPs to the total number of WDs (blue), (b) temporal evolution of the normalized occurrence anomalies of the contribution of different WPs to the total number of WDs for all European stations smoothed with a 5-yr RM, and (c) linear trends (% per decade) in the occurrence of WPs of different duration (green bars) along with their 95% significance (dark shaded bars).

in Scandinavia and decreases in the southeast direction being 1–2 days in the Southern Europe (no figure shown). This spatial distribution is quite robust since the interannual standard deviations of the durations range from 5 to 15% of the mean values.

[8] Figure 1b shows the temporal evolution of the normalized occurrence anomalies of the contribution of WPs to the total number of WDs (WP_n), derived from all European stations and smoothed with a 5-yr running mean. The occurrence anomalies were derived as $P'(x) = [P(x) - \bar{P}(x)]/\sigma[P(x)]$, where x is the WP_n for a given WP, $P(x)$ is the probability distribution for an individual year, $\sigma[P(x)]$ is the standard deviation of the probability distribution for a particular duration; $P'(x)$ is the normalized anomaly of the probability distribution and the bar being the averaging operator. Over the past 60 years the fractional contribution of the long WPs to the total number of WDs gradually increased (Figure 1b). Negative anomalies for long WPs during the 1950s and 1960s become primarily positive in the 1990s and 2000s while short WPs exhibit the opposite tendency.

[9] The negative linear trend for the number of short WPs and the remarkably positive trend for the occurrence of long WPs are both statistically significant (Figure 1c). Significance of linear trends in Figure 1c (as well as in the further analysis) was estimated using the Student t-test together with the non-parametric Mann-Kendall test and was also analyzed with respect to the confidence intervals of the trend significance (the reliability ratio [*Hayashi*, 1982]). Only trends satisfying all three criteria at 95% level were considered to be significant.

[10] The growing duration of WPs over the last 60 years constitutes a clear pan-European pattern. The linear trends in the WP duration (Figure 2a) over Central Western Europe, Scandinavia and European Russia are primarily positive, ranging from 2 to 4–5% per decade. Thus, the mean duration of WPs has increased in Western Europe by 0.6–0.7 days over 60 years and up to 0.5 days in European Russia. Negative trends of up to 3% per decade are observed in few locations in Southern, Western and Central Europe. Figures 2b and 2c clearly show the opposite tendencies in the number of short and long spells, quantified respectively by the 50th and 90th percentile of the WP durations. The actual increase of the duration of the longest 10% of WPs over 60 yr period is about 1 day for the Western and Eastern Europe.

[11] One can argue that the lengthening of WPs can be simply caused by changing total number of WDs rather than by regrouping of events from shorter into longer WPs. We applied Monte Carlo approach (earlier used to estimate the impact of missing data on trends [*Zolina et al.*, 2005]) to evaluate the net effect of the increase of WDs (regionally up to 3.6% per decade) on the trends in the WP duration. In the 3 groups of experiments (Table 1) we first simulated the observed change in the number of WDs by random generation of single WDs. This may result in a decreasing duration of WPs due to increasing frequency of 1-day events. Secondly, the events were generated according to the observed frequency distribution of WPs (Figure 1a). Finally, in an "extreme" simulation the observed change in the number of WDs was generated by one continuous WP. Table1 shows that the largest expected net effect from the change in the number of WDs even for the "extreme" unrealistic case may impose trends in the duration of WPs of only 0.02–0.16 days over 60 years. This is 4 to 9 times smaller than the observed changes in WP durations.

[12] How the lengthening of WPs influenced the intensity of precipitation? Conventional analysis shows that rain intensity and totals during 1950–2008 increased from 1.5–2.5% per decade in Northern Western Europe to 4% per decade in Eastern Europe in agreement with *Moberg et al.* [2006] and *Zolina et al.* [2009]. Figure 2d shows that the fractional contribution to precipitation totals from the relatively short WPs (<50th percentile, typically 1–2 days) decreased by 3–5% per decade with the strongest trend of −5% per decade in the European Russia. At the same time, the contribution to the totals from longer WPs (>50th percentile) increased almost everywhere from 1–3% per decade in Western Europe to 4–6% per decade in European Russia (Figure 2e). Thus the contribution by short WPs to the precipitation total decreased during 60 years from 46–48%

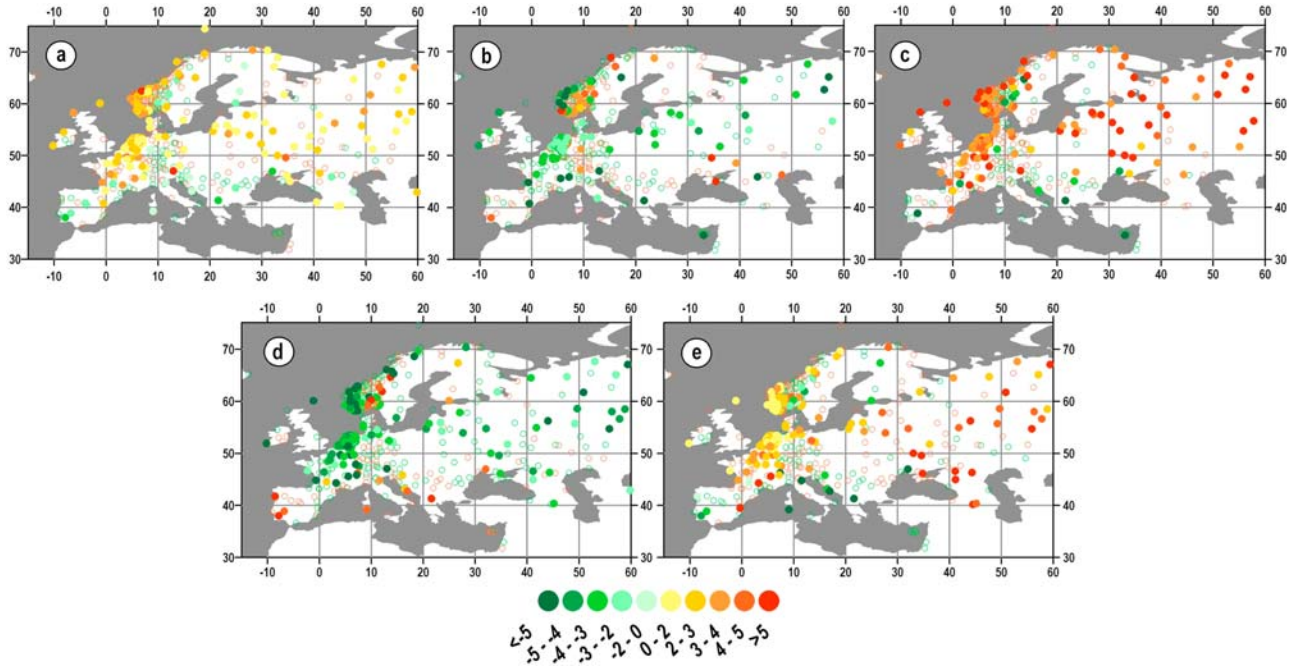

Figure 2. Linear trends (% per decade) (a) in the mean duration of WPs, in the duration of (b) very short (50th percentile) and (c) long (90th percentile) WPs, and in the fractional contribution to the precipitation totals from the (d) relatively short and (e) relatively long WPs. Closed circles show trends significant at 95% level.

to about 28–33%, while the contribution from the longer WPs increased from 50% in the 1950s to roughly 70% in the 2000s.

[13] In the next step we estimated the impact of increasing WP duration onto the changes in the intensity of heavy precipitation associated with different WPs. Intense events were quantified as those exceeding the 95th percentile estimated from the raw daily time series for which the 95th percentile threshold was computed from 60-year records. Results obtained using the Gamma distribution or the Extreme Value Distribution are very similar to those based on the raw data. The fractional contribution of heavy precipitation associated with different WPs to the precipitation total was computed as the contribution of the 5% of the most intense precipitation events [*KTK03*]. For annual series these estimates are very close to those obtained using the theoretically Distribution of Fractional Contribution [*Zolina et al.*, 2009].

[14] On average, the number of heavy precipitation events (exceeding 95th percentile) peaks for 2–3 day WPs (Figure 3a). Over Scandinavia this peak is shifted to 3–4 days and in European Russia the highest occurrence of intense rainfalls is associated with WPs of 1–2 days duration. Figure 3b shows the normalized fraction anomalies of heavy precipitation daily events occurring during WPs of different length, computed in the same manner as in Figure 1b. During 1950–2008 the occurrence of the association of heavy rainfall with longer WPs has increased by 3–4% per decade while the occurrence of heavy precipitation during shorter WPs (1–2 days) has decreased by 3% per decade. The percentage of heavy rainfalls associated with WPs shorter than 3 days decreased from 60% in the 1950s–1960s to 45% in the 1990s–2000s, while the occurrence of intense precipitation associated with longer WPs increased from 40% to 55%. Furthermore heavy rainfalls associated with longer WPs intensified over Europe with upward trends of 2–3% per decade in Western Europe and >5% per decade in European Russia (Figure 3c), implying actual changes from 4 to 9 mm/day over the 60-year period. Alternatively, the intensity of heavy precipitation events associated with shorter WPs either do not show any trend or locally decrease, e.g. in Central Europe, by 2–4% per decade (Figure 3d).

Table 1. Trends in the Duration of WPs Simulated in 3 Sensitivity Experiments for the Changes of the Number of WDs of 1%, 2%, 3% per Decade and Averaged Over All Stations[a]

Sensitivity Experiments	Simulated Trend in the Number of WDs (% per decade)		
	1%	2%	3%
Random generation of single WDs	0.004±0.006	0.009±0.017	0.013±0.022
Random generation of events according to the observed frequency distribution of the duration of WPs	0.084±0.051	0.131±0.089	0.197±0.114
"Extreme" unrealistic experiment (generation of the change in the number of WDs as one continuous wet spell)	0.171±0.102	0.314±0.193	0.471±0.254

[a]Actual positive trends in the number of WDs over Europe vary from 0.3 to 3.6% per decade.

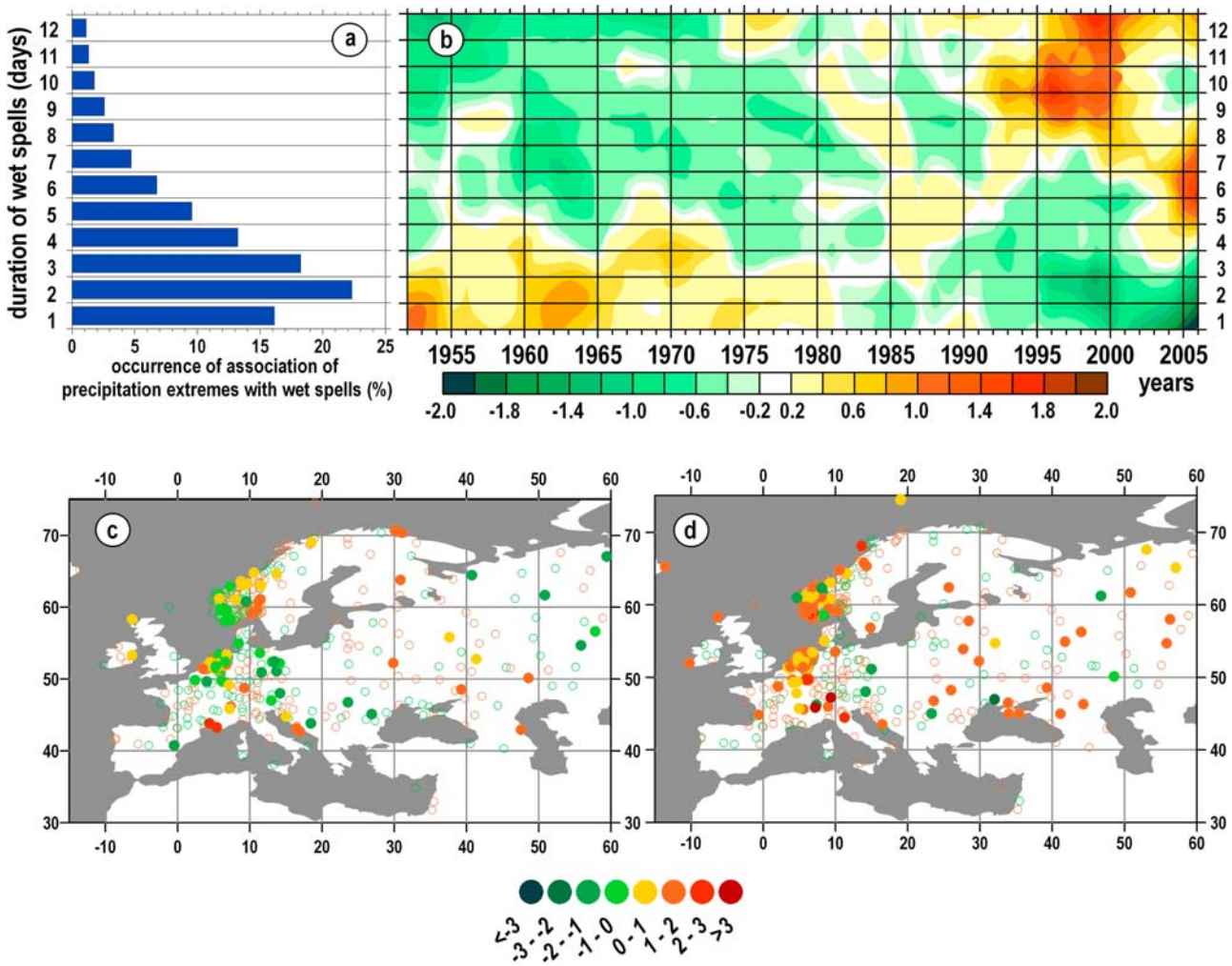

Figure 3. (a) The percentage of extreme precipitation events occurring during WPs of different durations, (b) temporal evolution of the normalized fraction anomalies of precipitation extremes occurring during different WPs smoothed with a 5-yr RM, and linear trends (% per decade) in the fractional contribution to the total of the intense events associated with (c) short and (d) long WPs. Closed circles show trends significant at 95% level.

[15] The influence of the increasing duration of European WPs over the last 60 years is summarized in 2-dimensional duration-intensity distribution (Figure 4). The occurrence of WPs longer than 2–3 days with high mean daily precipitation intensities have clearly increased (Figure 4), while short and moderately long WPs with precipitation <4 mm/day have decreased in frequency. Very similarly to the tendencies in the mean intensity, the intensity of heavy precipitation events (exceeding the 95th percentile and contributing 25 to 40% to the total) occurring during long wet spells increased by 6–8% per decade, while heavy rainfalls occurring during short WPs weakened by 4–6% per decade (no figure shown).

4. Summary and Conclusions

[16] Our analysis shows that European precipitation has not only increased and become more extreme during the last 60 years but also its structure has changed: short rain events have been regrouped into prolonged wet spells. Heavy precipitation events associated with longer WPs have intensified by about 12–18% during the last 60 years, while heavy rainfalls associated with short WPs became less intense. The lengthening of the European wet spells combined with an increased occurrence of associated heavy precipitation hints at an increasing role of moisture advection by cyclones in forming extremes with a pace exceeding that implied by local temperature changes [*Trenberth et al.*, 2003; *Allan and Soden*, 2008]. Direct association of cyclone activity with the duration of WPs requires analysis for individual seasons which is difficult due to the limited (to provide the robust statistics) number of WPs per season or month. In this respect an accurate derivation of the theoretical PDFs for the WP duration and associated intensity will provide good prospect for the further analysis.

[17] In the future the role of changing duration of WPs in forming precipitation trends, including the intensity and occurrence of heavy and extreme rainfalls should be investigated in climate model simulations. From the hydrologic perspective, it is important to account for the potential impacts of the changed precipitation regime on water resources and flooding. While there is no significant trend in flood frequencies for the past 80–150 years in Europe [*Mudelsee et al.*, 2003], a clustering of floods has occurred in the last

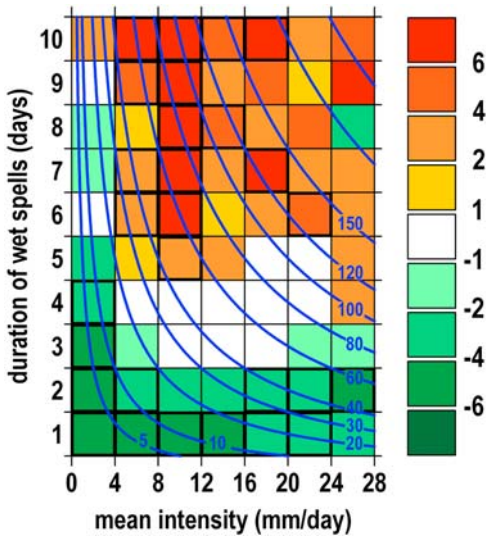

Figure 4. Trends (% per decade) in the frequency of WPs of different duration and mean intensities. Bold sided squares mark trends significant at the 95% level. Blue contours show precipitation totals for WPs of different durations and mean intensities.

decades [*Bunde et al.*, 2005]. Changing character of WPs may significantly alter change in the frequency and strength of floods. Lengthening of WPs will also enhance groundwater recharge and soil moisture storage [*Maxwell and Kollet*, 2008]. However, it is not easy to evaluate the transient hydrodynamic response at the catchment scale without integrated hydrologic simulations, accurately reproducing the variability across all spatiotemporal scales from days to decades and from meters to kilometers.

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References

Allan, R. P., and B. J. Soden (2008), Atmospheric warming and the amplification of precipitation extremes, *Science*, *321*(5895), 1481–1484, doi:10.1126/science.1160787.

Brommer, D. M., R. S. Cerveny, and R. C. Balling (2007), Characteristics of long-duration precipitation events across the United States, *Geophys. Res. Lett.*, *34*, L22712, doi:10.1029/2007GL031808.

Bunde, A., et al. (2005), Long-term memory: A natural mechanism for the clustering of extreme events and anomalous residual times in climate records, *Phys. Rev. Lett.*, *94*(4), 048701, doi:10.1103/PhysRevLett.94.048701.

Emori, S., and S. J. Brown (2005), Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate, *Geophys. Res. Lett.*, *32*, L17706, doi:10.1029/2005GL023272.

Frei, C., and C. Schär (2001), Detection probability of trends in rare events: Theory and application to heavy precipitation in the Alpine region, *J. Clim.*, *14*, 1568–1584, doi:10.1175/1520-0442(2001)014<1568:DPOTIR>2.0.CO;2.

Groisman, P. Y., and R. W. Knight (2008), Prolonged dry episodes over the conterminous United States: New tendencies emerging during the last 40 years, *J. Clim.*, *21*, 1850–1862, doi:10.1175/2007JCLI2013.1.

Groisman, P. Y., et al. (2005), Trends in intense precipitation in the climate record, *J. Clim.*, *18*(9), 1326–1350, doi:10.1175/JCLI3339.1.

Hayashi, Y. (1982), Confidence intervals of a climatic signal, *J. Atmos. Sci.*, *39*, 1895–1905, doi:10.1175/1520-0469(1982)039<1895:CIOACS>2.0.CO;2.

Klein Tank, A. M. G., and G. P. Koennen (2003), Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99, *J. Clim.*, *16*, 3665–3680, doi:10.1175/1520-0442(2003)016<3665:TIIODT>2.0.CO;2.

Klok, E. J., and A. M. G. Klein Tank (2009), Undated and extended European data set of daily climate observations, *Int. J. Climatol.*, *29*, 1182–1191, doi:10.1002/joc.1779.

Kunkel, K. E., K. Andsager, and D. R. Easterling (1999), Long-term trends in extreme precipitation events over the conterminous United States and Canada, *J. Clim.*, *12*, 2515–2527, doi:10.1175/1520-0442(1999)012<2515:LTTIEP>2.0.CO;2.

Kunkel, K. E., D. R. Easterling, K. Redmond, and K. Hubbard (2003), Temporal variations of extreme precipitation events in the United States: 1895–2000, *Geophys. Res. Lett.*, *30*(17), 1900, doi:10.1029/2003GL018052.

Maxwell, R. M., and S. J. Kollet (2008), Interdependence of groundwater dynamics and land-energy feedbacks under climate change, *Nat. Geosci.*, *1*, 665–669, doi:10.1038/ngeo315.

Moberg, A., et al. (2006), Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000, *J. Geophys. Res.*, *111*, D22106, doi:10.1029/2006JD007103.

Mudelsee, M., et al. (2003), No upward trends in the occurrence of extreme floods in central Europe, *Nature*, *425*(6954), 166–169, doi:10.1038/nature01928.

Scaife, A. A., C. K. Folland, L. V. Alexander, A. Moberg, and J. R. Knight (2008), European climate extremes and the North Atlantic Oscillation, *J. Clim.*, *21*, 72–83, doi:10.1175/2007JCLI1631.1.

Schmidli, J., and C. Frei (2005), Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century, *Int. J. Climatol.*, *25*, 753–771, doi:10.1002/joc.1179.

Semenov, V. A., and L. Bengtsson (2002), Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM, *Clim. Dyn.*, *19*, 123–140, doi:10.1007/s00382-001-0218-4.

Trenberth, K. E., et al. (2003), The changing character of precipitation, *Bull. Am. Meteorol. Soc.*, *84*, 1205–1217, doi:10.1175/BAMS-84-9-1205.

Zolina, O., C. Simmer, A. Kapala, and S. K. Gulev (2005), On the robustness of the estimates of centennial-scale variability in heavy precipitation from station data over Europe, *Geophys. Res. Lett.*, *32*, L14707, doi:10.1029/2005GL023231.

Zolina, O., C. Simmer, A. Kapala, S. Bachner, S. K. Gulev, and H. Maechel (2008), Seasonally dependent changes of precipitation extremes over Germany since 1950 from a very dense observational network, *J. Geophys. Res.*, *113*, D06110, doi:10.1029/2007JD008393.

Zolina, O., C. Simmer, K. Belyaev, A. Kapala, and S. K. Gulev (2009), Improving estimates of heavy and extreme precipitation using daily records from European rain gauges, *J. Hydrometeorol.*, *10*, 701–716, doi:10.1175/2008JHM1055.1.

S. K. Gulev, P. P. Shirshov Institute of Oceanology, 36, Nahimovski prospect, Moscow, 117997, Russia.

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