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Exploring the relationship between changes in climate and floods using a model-based analysis

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[1] A model-based approach is implemented to attribute changes in the seasonal extreme river flows to meteorological drivers. A semidistributed model that simulates daily runoff from daily series of meteorological variables was employed together with a multisite, multivariable weather generator. Ensembles of synthetic meteorological variables were synthesized using the weather generator and were used to drive the hydrological model. In order to systematically assess the relative importance of each of the meteorological variables in explaining the detected changes in the flood behavior, the variables were generated by accounting for the year to year variability of the distribution of one of the variables at a time while keeping the distributions of the others temporally stationary. The approach was tested on eight case study catchments from different parts of Germany. The results show the ability of the approach in identifying the meteorological variable that is associated with the detected change in the extreme flow. Changes in precipitation were found to be the major meteorological drivers of the trends detected in the seasonal extreme flows in most of the investigated catchments. Temperature was found to be less important in explaining any of the changes in all catchments.

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1. Introduction

[2] A number of recent studies conducted in different parts of the world have revealed the existence of trends in the observed extreme river runoff over the past several decades [e.g., *Adamowski and Bocci*, 2001; *Lindström and Bergström*, 2004; *Kundzewicz et al.*, 2005; *Petrow and Merz*, 2009]. There is a widespread speculation that such changes may have been driven by climate related changes. Several studies carried out on hydrometeorological variables have also indicated progressive changes in the extremes of temperature and precipitation [e.g., *Haylock and Goodess*, 2004; *Aguilar et al.*, 2005; *Hundecha and Bárdossy*, 2005; *Schmidli and Frei*, 2005].

[3] Understanding the likely causes of the changes in extreme flows is an important step in reviewing existing flood risk management practices and adapting future practices to cope with the flood risk under a changing environment. Several studies were carried out in the past to investigate the relationship between changes in river flow and changes in the meteorological driving or climate related phenomena as a basis of attributing the changes in the river flow to climate related changes. The approaches followed by the studies are broadly classified into two groups [see, e.g., *Blöschl et al.*, 2007].

[4] The first group of approaches is based on a statistical examination of changes in the meteorological driving or large scale climate indices and comparing them with the corresponding changes in the runoff statistics. *Robson et al.* [1998] investigated the existence of trends in the national flood count and maximum annual flood for the United Kingdom by pooling data across all available stations. Although they did not find any marked trend over the entire investigation period, they observed systematic variation in the year-to-year variability of the flood behavior that closely resembles the corresponding variability in precipitation. Similarly, *Novotny and Stefan* [2007] analyzed river flow data from rivers in Minnesota for trends in different indices of flow in order to attribute the detected changes to regional precipitation change by examining the existence of trends in precipitation over regions corresponding to the stream. Additionally, they studied the correlation between the mean annual streamflow and annual precipitation. Also, *Stewart et al.* [2005] investigated changes in timing of snowmelt and fractional monthly and seasonal flows in snowmelt dominated flow seasons and tried to attribute the changes to changes in regional precipitation and temperature through a correlation analysis. *Cunderlik and Burn* [2004] investigated the link between a regional trend in monthly maximum flows of South British Columbia and climate variables by computing the regional trends using a regional bootstrap technique and comparing the similarity of the regional trends in the flow and climate variables. As a measure of plausibility of the link between the two, they studied the cross correlation between the observed series of the flow and the climate variables. *Aguado et al.* [1992] assessed the relative impact of temperature and precipitation on changes in the proportion of streamflow occurring in a given season by implementing multiple regression

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between fractional streamflow and the corresponding seasonal precipitation and temperature in basins in Northern California and Southern Oregon. *Dettinger and Cayan* [1994] tried to attribute the shift in the timing of runoff in the same region to increasing decadal and interannual trends in winter temperature. They further investigated the existence of concurrent trends in large scale atmospheric circulations that could have led to the increasing trend in winter temperature.

[5] In the second group, hydrological models are implemented to investigate the sensitivity of runoff and other state variables to changes in the meteorological drivers, thereby providing a framework for attributing changes in runoff to meteorological drivers. *Hamlet and Lettenmaier* [2007] investigated the sensitivity of flood risk in the western United States to changes in winter temperature as well as to climatic variations associated with PDO and ENSO. To this end, they implemented a hydrologic model driven by observed precipitation and detrended temperature series. For the same region, *Hamlet et al.* [2007] investigated the existence of trends in evapotranspiration, soil moisture, and runoff of spring and summer as well as their timing by simulating them using a hydrological model. They investigated the trends of the simulated series and tried to attribute the detected changes either to regional warming or precipitation variability. They studied the relative contribution of the temperature and precipitation variability by setting the precipitation and temperature series, respectively, to the monthly climatological values while keeping the observed variability of the other.

[6] Particular caution needs to be taken in trying to attribute changes in extreme flows to meteorological drivers. While a change in the meteorological variables can potentially result in a change in extreme river flow, attributing changes in extreme flow directly to changes in regional extreme meteorological variables is not straightforward because of a complex dynamical relationship between them. Generation of extreme flows is influenced by the spatial distribution of the variables and their temporal dynamics. For instance, the traditional approach of comparing trends in the catchment average precipitation with trends in the catchment outflow as a basis of attributing changes in extreme flows to changes in precipitation can potentially lead to a wrong conclusion. Identifying the appropriate spatial pattern of distribution of precipitation that results in critical flow conditions at the catchment outlet is not straightforward. Intense convective precipitation falling on parts of the catchment may lead to flooding while frontal precipitation falling over the entire catchment which has the same catchment average value over a similar time scale may only produce a flow which is contained well below the bankfull depth of the river.

[7] The temporal scale of the precipitation that produces floods is also dependent on the size of the catchment and other characteristics, such as catchment initial states, and comparing the trend of the catchment scale annual maximum daily precipitation with the corresponding trend in the annual maximum flow could be misleading. *Pinter et al.* [2006] attempted to address this problem by studying the correlation coefficients between flood peaks and cumulative basin precipitation of different durations prior to the peak (1–30 days) for the Rhine basin at the gauge Cologne. They found a maximum correlation for 10 day antecedent precipitation, which they then used as flood-producing duration of precipitation. Finally, changes in the 10 day maximum precipitation were compared to changes in flood peaks, and it was concluded that the increase in flood magnitude and frequency has been driven in part by an increase in this flood-causing precipitation. Although such approaches may lead to some rough understanding of the drivers of changes in flood behavior, they are not fully capable of unraveling the relationship between meteorology and flood flows. The relationship is modulated by several factors, such as catchment state, characteristics of the flood-triggering precipitation event (e.g., duration, within-storm variability), or catchment characteristics (e.g., spatial distribution of runoff generation processes). These factors may vary from event to event, from season to season and from region to region. There is no single measure of meteorology that correlates highly with flooding. This missing link hinders the detection and attribution of changes in flood magnitude to meteorological drivers using the traditional statistical comparison approach.

[8] In this paper, we propose an alternative approach that could be used to evaluate the hypothesis that changes in the distribution of meteorological drivers are behind the changes detected in daily extreme river flows. It essentially belongs to the second group of approaches for the detection and attribution of changes in river flows. We make use of a multisite, multivariable weather generator to synthesize weather variables that are required to drive a hydrological model by keeping the changes in the distributions of the observations so that any trends are reproduced in a spatially consistent way. Ensembles of daily river flows are simulated using a semidistributed hydrological model driven by the variables thus generated. The structure and parameterization of the hydrological model are held constant throughout the simulation period. Hence, the hydrological model represents a stationary hydrological system, and trends in the simulated maximum flows are caused by temporal changes in the meteorological forcing of the model. In addition, the method allows us to reveal the relative importance of the changes in precipitation and temperature in the detected changes in extreme flows. The weather generator allows us to generate a large number of meteorological forcing so that the effect of natural variability on flood trends is taken into account. We implement the proposed approach for the analysis of changes in the seasonal daily extreme flows in eight mesoscale catchments in Germany.

2. Study Area and Data

[9] The study was carried out on eight mesoscale catchments from different parts of Germany (Figure 1). They were selected on the basis of the presence of trends in the seasonal daily maximum flows (see section 4.3 for details of the trend test). The trends were computed on a two season basis: winter (November–April) and summer (May–October). Significant trends at 10% were detected in the seasonal maximum flows at least in one of the seasons. Furthermore, the choice was guided by the intent to cover different regions within Germany that fall within different climate regimes. Their area varies from 843 to 15,037 km^2. For ease of application of the hydrological model, each of

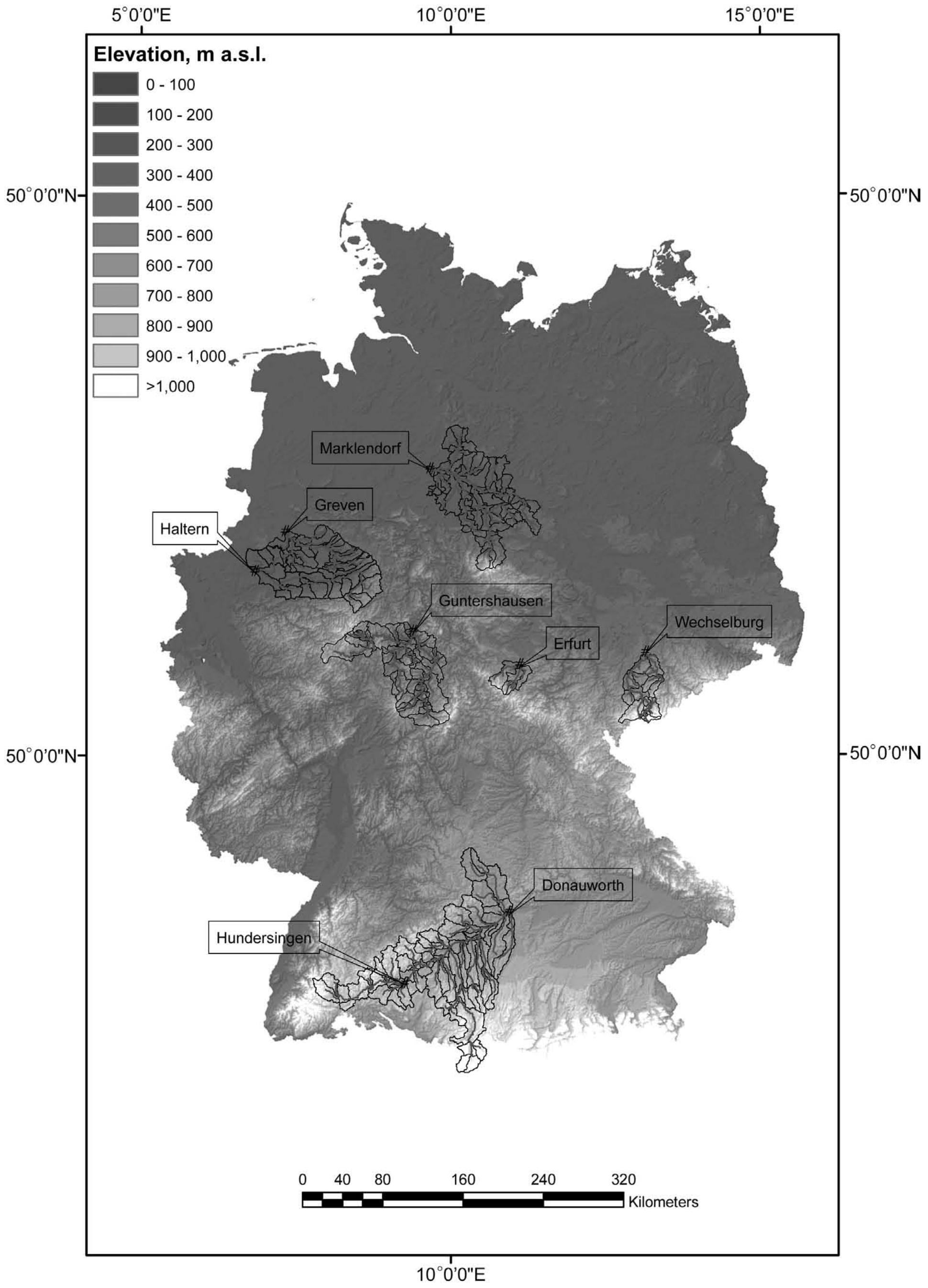

Figure 1. The test catchments used in the study subdivided into smaller subcatchments.

them was subdivided into smaller subbasins as shown in Figure 1.

[10] The selected catchments generally lie within different climate and flood regimes and have different morphological and land use characteristics. *Beurton and Thieken* [2009] identified three regions of homogeneous flood regimes (A, B, and C) within Germany by analyzing annual maximum flows from 481 stations across Germany. The regime zones and other important characteristics corresponding to each of the investigated catchments are shown in Table 1. The central and western parts of Germany (regime A), to which the river catchments of Lippe, Ems, and Fulda belong, are dominated by winter flooding. This region is characterized by a maritime Atlantic climate influenced by westerly winds with associated midlatitude cyclone rainfall over large spatial extent. The temperature in the region rarely falls below freezing point and the runoff regime is mainly pluvial. However, the southern part of the Fulda catchment is influenced by the continental climate of eastern Europe and the runoff from the mountainous areas is pluvio-nival, with many flood events in spring resulting from snow melt.

Table 1. Typical Physical Characteristics of the Investigated Catchments[a]

Gauge	Size (km^2)	Regime	Mean Slope (%)	Elevation (m asl)			TC (days)	Land Use (%)					Predominant Soil Texture	Dams
				Minimum	Mean	Maximum		Urban	Agriculture	Forest	Pasture, Grass	Others		
Haltern	4273	A	3.7	36	144	627	2.84	9.9	63.4	16.6	9	1.1	brown silt, sand	yes
Greven	2842	A	2.5	32	84	398	3.12	9.7	74.3	10.6	4.7	0.7	sand, loamy silty brown soil	no known
Guntershausen	6366	A	11.1	132	377	950	2.7	4.4	36.4	43.2	15.5	0.5	loamy sand, to silty loam brown soil	yes
Marklendorf	7209	B	3.2	24	104	1145	3.88	7.9	50.7	32	8.4	1	sand, brown silty soil	yes
Erfurt	843	B	9.6	218	443	970	0.6	6.9	43.3	39.4	9.8	0.6	loam and clay, loamy-sand rocky brown soil	yes
Wechselburg	2107	B	8.7	171	494	1200	1.4	14.8	43.6	35.2	5.6	0.8	silty loam brown soil, loamy sand brown soil	yes
Hundersingen	2639	B	11	542	773	1151	1.64	6	30.3	46.7	16.6	0.4	loamy clay, silty loam brown soil	yes
Donauworth	15,037	C	8.6	392	647	2587	4.09	5.4	39	32.6	21.8	1.2	loamy clay, silty loam brown soil	yes

[a] Land use is in percent of total area. TC, time of concentration (estimate made by the preprocessor of the hydrological model SWIM); asl, above sea level.

[11] The northern and eastern parts (regime B) are characterized by flooding in winter that extends further to spring, with the maximum flood count shifting to spring. Climatologically, this region is similar to regime A, but with a gradual shift from the maritime climate of western Europe to the continental climate of eastern Europe, which is characterized by cool winters and warm summers. The winter floods are mainly caused by the westerly wind dynamics like in regime A. Snow is usually formed in winter, especially in the mountainous areas and spring floods are accounted for melt of such snow accumulated during winter. There are also more flooding events in summer in regime B compared to regime A, which are usually caused by intense torrential summer storms. The Aller, Gera, Zwickauer Mulde, and the upper part of the Danube belong to this regime.

[12] The southern part (regime C), on the other hand, is predominantly flooded in summer, although spring and winter also contribute considerable flood events. Parts of the drainage area of this regime are located in the Alpine forelands and northern Alps. These regions are characterized by freezing temperatures over the winter period, leading to long-lasting snow retention. Melt water is available in late spring and summer, which leads to a shift of the flooding season to late spring and summer. Parts of the Danube catchment belong to this regime and the gauge Donauworth is influenced by tributaries that drain the Alpine and Alpine forelands, although the upstream part of the catchment belongs to regime B. Figure 2 shows the relative frequency of occurrence of annual maximum flows in different months in the selected catchments, which generally shows consistency with the flood regime zoning.

[13] The land use and morphological characteristics of the catchments are also variable. Both the Lippe and Ems catchments have low-relief terrain and their land use structure is predominantly agricultural. On the other hand, the Fulda catchment has some mountainous areas in the upstream regions and the land use in these regions is mainly forest. In the lowland areas, the main land use is agricultural. The southern edge of the Aller catchment rises to an elevation of more than a 1000 m but rapidly declines to less than 300 m and most part of the catchment is of low terrain. The mountainous areas and the northern parts of the catchment are predominantly forest covered, while the other regions are mainly agriculturally used. Similarly, the Gera and Zwickauer Mulde catchments are characterized by mountainous terrain in the very upstream regions, with a predominantly forest cover and lowlands elsewhere with agricultural land use structure. Part of the Danube investigated in this work has a more complex topographic structure. The Southern part is the Alpine region with very high elevation and slopes steeply toward the north and north east. Part of the catchment to the left side of the main channel is of gentle slope. The very upstream of the catchment is part of the Black forest and the major part of the Alpine area is forest covered. Elsewhere, both agricultural and forest covers characterize the catchment (see Table 1).

[14] Daily meteorological data (precipitation amounts, maximum and minimum temperature, relative humidity, and sunshine and total cloud cover durations) were obtained from the German Weather Service (DWD) from 2342 stations covering the entire Germany. Solar radiation is required in the present work. However, measured data

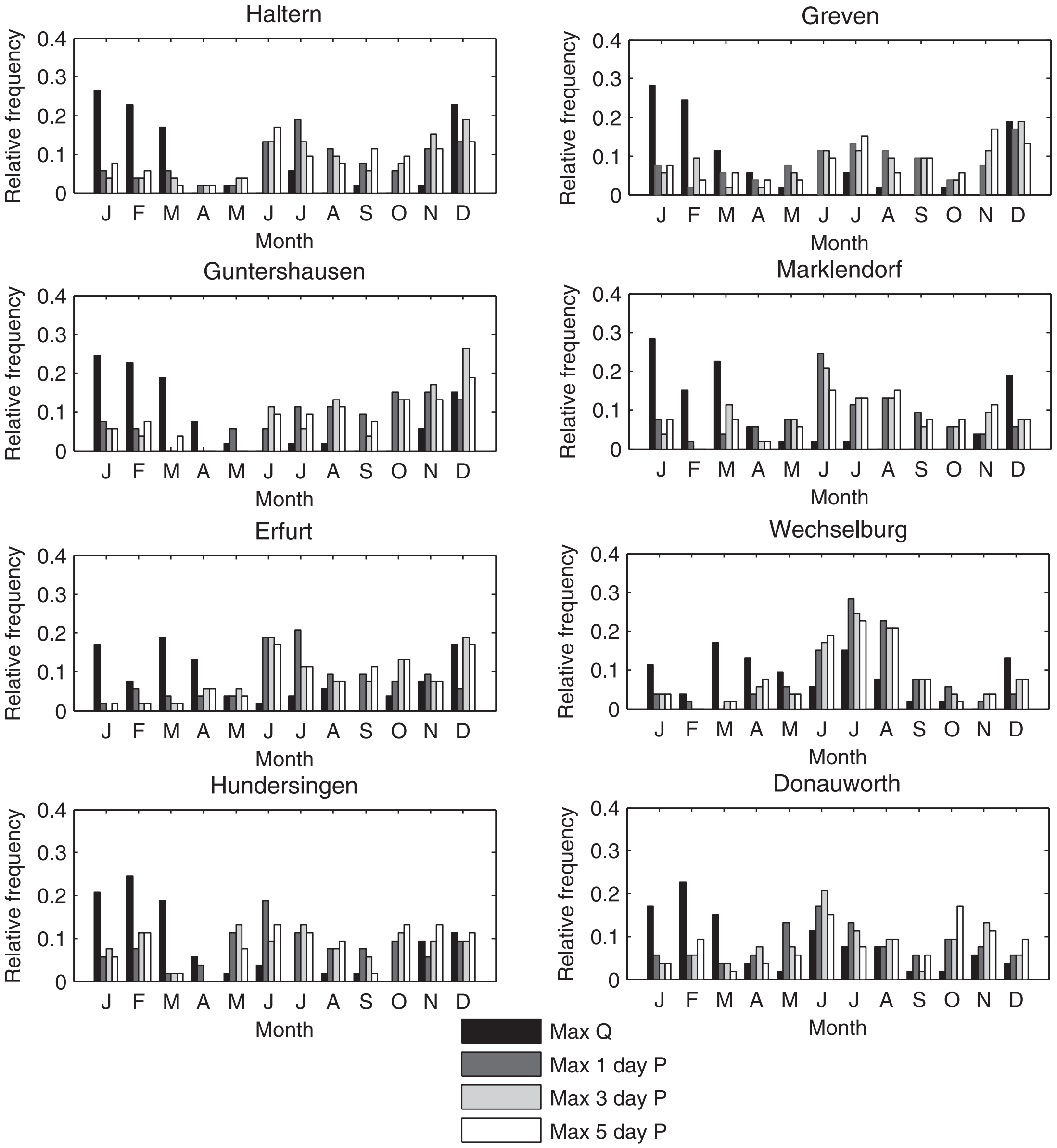

Figure 2. Monthly distributions of the proportion of annual maximum flood flows and catchment average maximum precipitation over different time scales.

were not available at all stations and the available measurements were not complete. It was derived using a regression-based approach from sunshine and cloud cover durations, as well as diurnal temperature range and total cloud cover [*Oesterle*, 2001]. Stream flows at the outlet gauges were obtained from the water authorities in charge of the runoff data. Since the data are part of the hydrometric observation network of the water authorities in Germany, the observations are regularly checked and can be assumed to be of good reliability. The observation period varies for the different stations. The analysis in this paper was carried out for the period 1951–2003, which corresponds to a common period for the data from different sources. In addition to hydrometeorological data, a number of digital data were acquired from different sources. A detailed soil map for the entire Germany (BÜK 1000 N2.3) was obtained from Bundesanstalt für Geowissenschaften und Rohstoffe (BGR). A European Soil Database map for the entire Europe was also obtained from the European Commission's Land Management and Natural Hazards unit. The CORINE land cover map and the SRTM digital elevation maps were also used in the study.

3. Methodology

[15] The methodology implemented in this work comprises a semidistributed mesoscale hydrological modeling for the simulation of daily runoff, implementation of a multisite weather generator for the simulation of synthetic meteorological variables, and a nonparametric trend test to detect trends in the seasonal maximum runoff as well as observed precipitation.

3.1. Hydrological Modeling

[16] The mesoscale rainfall-runoff model SWIM [*Krysanova et al.*, 1998], developed for the modeling of the dynamics of water, nutrients, and sediment at a watershed scale, is implemented. The model is semidistributed and has a three-level spatial disaggregation scheme. A watershed is the primary unit of modeling and is subdivided into subbasins, which are further subdivided into hydrological response units on the basis of topography, soil types, and land use classes. Runoff is computed on the basis of the SCS curve number method and the model has routines for the computation of snow accumulation and melt, evapotranspiration, percolation, subsurface runoff from a soil column, and groundwater runoff. A degree-day method is employed for the computation of snow accumulation and melt. Potential evapotranspiration is computed using the Priestley-Taylor method [*Priestley and Taylor*, 1972] from solar radiation and air temperature. Actual evapotranspiration is estimated by adjusting the potential evapotranspiration on the basis of the leaf area index and actual soil moisture. Percolation is computed using a conceptual storage routing technique and is governed by the saturated hydraulic conductivity of the soil layer. Subsurface flow from the soil zone is computed when the storage in the layer exceeds the field capacity, as a function of the soil hydraulic conductivity. The runoff component from the groundwater is computed as a linear function of the rate of change of the water table through recharge from the soil zone. The model is driven by daily precipitation, air temperature and solar radiation and produces daily mean runoff from subbasins. The Muskingum flood routing method is implemented to route the generated runoff along the channel.

3.2. Multisite, Multivariable Weather Generator

[17] To investigate whether the detected trends in the extreme runoff are related to changes in meteorological drivers, spatially and temporally consistent synthetic meteorological drivers were generated using a multisite, multivariable stochastic weather generator. The number of weather stations used in this study varies in the different catchments (see Table 6). The weather generator has two components. The first component generates daily precipitation series at multiple sites using a multivariate-autoregressive model. Since this study is focused on extremes, appropriate distributions that capture the extremes of daily precipitation have to be employed. Typically, a Gamma distribution has been used to model daily precipitation. However, previous studies have shown that, although a Gamma distribution fits well to the bulk of the data, it usually underestimates the extremes of daily precipitation [*Wilks*, 1999a; *Vrac and Naveau*, 2007; *Furrer and Katz*, 2008; *Hundecha et al.*, 2009]. Therefore, a mixture of Gamma and generalized Pareto distributions (GPD), which improves the characterization of the extremes, is employed in this work. It uses dynamically varying weights to mix the two distributions [*Vrac and Naveau*, 2007; *Hundecha et al.*, 2009]:

$$f(z,u) = \frac{[1-p(z,u)]h(z,u) + p(z,u)g(z,u)}{K(u)} \qquad (1)$$

where $f(z, u)$ is the probability density function of the daily precipitation z at location u, $p(z, u)$ is the mixing weight, $K(u)$ is a normalizing constant that ensures the area under $f(z, u)$ is unity, and $h(z, u)$ and $g(z, u)$ are the pdf's of the Gamma and GPD, respectively. The mixing weight $p(z, u)$ is given by

$$p(z,u) = \frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{z-\nu(u)}{\tau(u)}\right) \qquad (2)$$

where $\nu(u) > 0$ and $\tau(u) > 0$ are the location and steepness parameters, respectively.

$$K(u) = 1 + \frac{1}{\pi}\int_0^\infty [g(z,u) - h(z,u)]\arctan\left(\frac{z-\nu(u)}{\tau(u)}\right)dz \qquad (3)$$

[18] The distribution is fitted to each station data on a monthly basis. The temporal and spatial dependence structures of precipitation are accounted for through the spatial and autocovariances of the observed precipitation computed after transforming the values at each station into a truncated standard normal variate. Transformation of the data into a normal space is done since the dependence structure between the individual elements of the multivariate normal distribution is fully described by the covariance matrix. Truncation is performed to account for dry days on the basis of the proportion of dry days. A multivariate autoregressive model is then applied to generate correlated synthetic values drawn from a standard normal variate at all stations, which are finally back transformed to the appropriate distribution fitted to the data at each station. Since the model is stochastic, one should also note that it is possible that the simulated values display spatial intermittence during a synoptic scale event although the model keeps the spatial covariance. More details of the model are presented by *Hundecha et al.* [2009].

[19] The second component generates minimum and maximum temperature, dew point temperature, and solar radiation at multiple stations using a similar principle as the precipitation model. A multisite extension of the Richardson type [*Richardson*, 1981] of weather generator is employed. This basically involves employing a multivariate autoregressive model on a vector of size four times the number of stations (four variables at each station). Such an approach was applied by *Wilks* [1999b, 2009], where normal distributions were fitted to all the variables. We employ normal distributions to the temperature values. *Parlange and Katz* [2000] demonstrated the improvement over the assumption of normality of solar radiation when they employed a square root transformation to the Pacific Northwest solar radiation data, although they found out that a reflected logarithmic transformation could be more suitable depending on the season. In this work, we found a square root transformation to offer adequate improvement. Normal distributions were then fitted to the transformed values. Similar to precipitation, distributions were fitted on a monthly basis. Furthermore, the distributions were fitted conditional to whether the day was wet or dry. Similar simplifications discussed by *Wilks* [1999b] were implemented to handle possible internal inconsistencies in the spatial-temporal correlation matrices.

Figure 3 shows a schematic representation of the entire weather generator employed in this work.

3.3. Attribution of Changes in Flood Flow to Changes in Climate Drivers

[20] To attribute the trends detected in the seasonal maximum flow to changes in the meteorological driving, the weather generator and the hydrological model were applied systematically. This basically involves generating ensembles of meteorological drivers using the weather generator instead of just one realization (the observations) to drive the hydrological model with so that one can estimate the distribution of the trend test statistic of the simulated extreme flow. Analysis of the distribution of the test statistic will reveal whether meteorological variables have resulted in significant change in extreme flow. The weather generator was applied using different assumptions on the distributions of the meteorological drivers. First, the meteorological variables were generated under the assumption of stationarity. For each weather parameter at each station, an appropriate distribution, as discussed in section 3.2, is fitted to the daily values from the entire data series on the monthly basis. Any trends in the original series are destroyed in the generated synthetic series and the new series is therefore essentially stationary. The runoff series generated by the hydrological model, which in turn was driven by stationary meteorological time series, is used to evaluate whether there are any inconsistencies in the model's ability to reasonably reflect changes in its driving. If a trend is still detected in the generated runoff, it is assumed that the model produces a trend that is not caused by an external climate driver and therefore will not be used for the investigation of the impact of changes in meteorological drivers on changes in runoff.

[21] In the second phase of application, synthetic precipitation series are generated in such a way that any trend in the observed series at each site is reproduced. To this effect, an appropriate distribution is fitted to the daily values of each year on the monthly basis. In order to get enough data to fit a distribution with and smooth the variation, daily data of the given month from five consecutive years centered on the year under consideration were used. The model parameters are estimated accordingly for each year on the monthly basis. The generated synthetic series reproduces the year to year dynamics of the distribution of daily precipitation over the observation period. Stationary series of temperature and radiation are generated by conditioning them on the generated precipitation. Analysis of the runoff generated through driving the hydrological model with the meteorological series generated in this way enables to detect changes in the runoff that are attributable to changes in precipitation. Similarly, in order to detect changes in runoff that are attributable to changes in temperature, the temperature and radiation series are generated using distributions that change over the years but conditioned on the state of the stationary synthetic

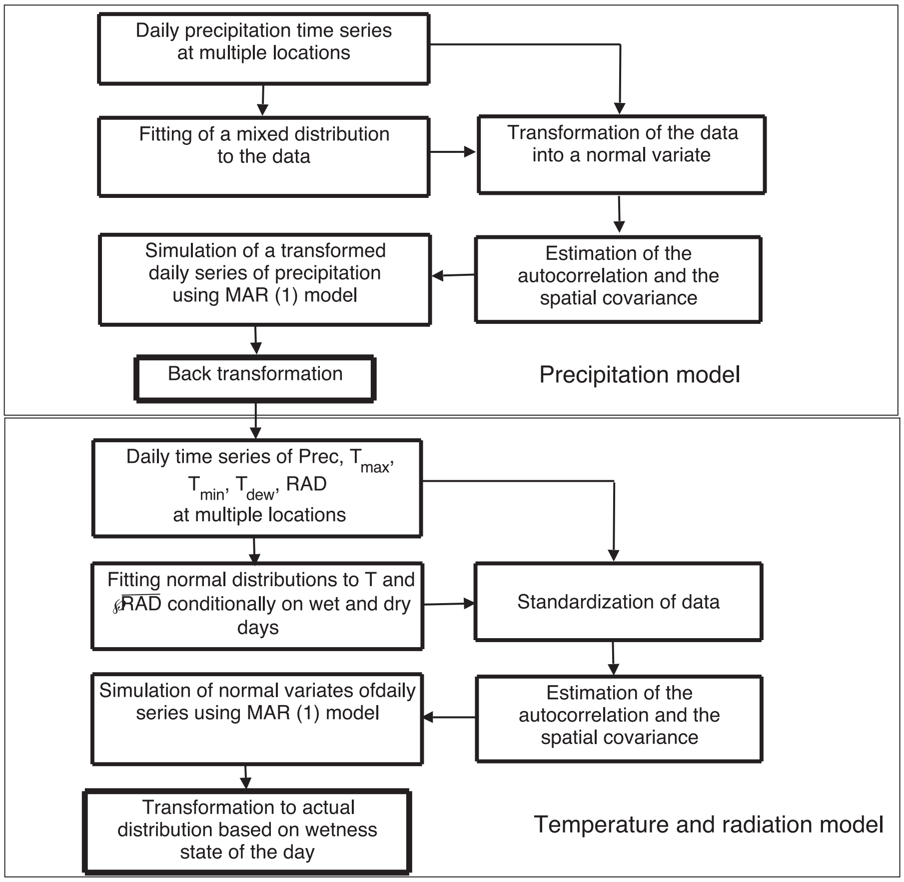

Figure 3. Schematic representation of the weather generator employed in the study.

precipitation series. The hydrological model is then driven by the temperature series thus generated and the stationary precipitation series. Finally, the effect of possible changes in both precipitation and temperature on the runoff is investigated by generating all weather variables whose distributions vary from year to year. Note that the synthetic series are generated in all cases for the same period as the observation.

3.4. Assumptions and Limitations

[22] It should be noted that there are some basic assumptions and simplifications that need to be applied in the proposed methodology. In the present work, only the effect of variability of daily meteorological variables on the change in the extremes of daily mean runoff is investigated. Although most of the catchments selected for the study are sufficiently large, with response times greater than a day except the catchment draining to Erfurt, the possible effect of the variability of the meteorological drivers at subdaily time scales is not considered.

[23] In addition, the detected changes in the extreme flow could have different sources that may include nonstationarities in the nonclimate factors, such as land use changes, introduction of river training works, as well as reservoirs whose operation rules are unknown. Since we did not have detailed information on these nonclimate factors, we kept all the nonclimate catchment properties stationary in the hydrological model. Ignoring such nonstationarities could be problematic in comprehensively attributing the changes in the streamflow to their drivers. The objective of the present work is however limited to investigating whether changes in the distributions of the meteorological drivers have contributed to the detected changes in the flow extremes. To achieve this, we had to rely on parameterizing the hydrological model in such a way that the model simulates the observed runoff at the catchment outlet reasonably well given the observed meteorological drivers. This is based on the assumption that the overall effects of all the nonclimate effects are implicitly represented through the model parameters. Data on land use dynamics and reservoir operations would have provided us with additional constraints to model calibration. Since the model parameters interact with one another, the additional information would not enable us to uniquely estimate the model parameters except possibly leading to improvement of the model performance. Although the impact of the parameter interaction could be studied using uncertainty analysis, we did not carry out this because of the computational demand the methodology we employed puts.

[24] If, despite the above limitations, one assumes that the hydrological model adequately simulates the flow when driven by climate drivers whose variability is within that of the observations, it may then be used as a stationary reference model to investigate whether changes in the distributions of the meteorological drivers translate into a significant trend in the extreme flow. Any change that is detected in the simulated extreme flow through representation of the dynamics of the distributions of the meteorological variables will be used as evidence that meteorological variables have contributed to a significant change in the extreme flow and not as the exclusive drivers of the change. Whether nonclimate factors have contributed to the detected change in the extreme flow cannot be deciphered using our setup.

4. Results and Discussion

4.1. Calibration and Validation of the Hydrological Model

[25] The hydrological model was calibrated over the period 1981–1989. The model calibration was carried out using daily discharge at the outlet gauge of each of the eight catchments. An automatic calibration was performed using the SCE-UA algorithm [*Duan et al.*, 1992]. A normalized weighted sum of the square of the differences between the observed and simulated discharge (NS) was employed as objective function. The weight at each time step was set to the observed discharge to give more emphasis to higher flows. The resulting objective function is similar to the well-known Nash-Sutcliffe efficiency measure [*Nash and Sutcliffe*, 1970] except for the weights [*Hundecha and Bárdossy*, 2004; *Hundecha et al.*, 2008].

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{N} w(\cdot)\Big(Q_c(t_i) - Q_0(t_i)\Big)^2}{\sum_{i=1}^{N} w(\cdot)\Big(Q_0(t_i) - \overline{Q}_0\Big)^2} \tag{4}$$

where $Q_c(t_i)$ and $Q_0(t_i)$ are the simulated and the observed discharges, respectively, at time t_i and $\overline{Q}_0$ is the mean observed discharge over the simulation period (N days), $w(\cdot)$ is a weight, which is equal to the observed discharge $Q_0(t_i)$.

[26] Seven parameters, which were found to be generally sensitive, were calibrated: two parameters of the Muskingum channel routing, two parameters of the degree-day snow melt process, two parameters controlling the subsurface flow contribution to the streamflow, and a parameter to fine tune the saturated hydraulic conductivity of the soil layer that was read from the soil database. However, the degree of sensitivity of some of the parameters is variable from region to region. For instance, the snow melt parameters are not that sensitive in the Lippe and Ems catchments, where as they are highly sensitive in the Danube, reflecting how important the snow process is in the runoff regime of the catchments.

[27] Table 2 summarizes the model performance at the eight gauges. In addition to the goodness of fit measure used for calibrating the model, the conventional Nash-Sutcliffe efficiency, mean bias as percentage of the observed mean flow, and peak error (see the footnote in Table 2 for estimation technique) were computed. On the basis of both the conventional and the weighted Nash-Sutcliffe efficiency measures, the model performance in all basins is acceptable. The absolute bias is also in most catchments below 10%. Only at Erfurt and Hundersingen the bias gets slightly greater than 10%. The peaks are generally a bit underestimated in most catchments with a maximum underestimation of 16% at Donauworth. Also, Figure 4 shows scatterplots of the simulated and observed daily flows over the entire period at each station. One can see from Figure 4 that the model captures the observed flows well. Figure 4 also shows that the very extreme flows are in most catchments a bit underestimated. On the basis of the objective measures and visual evaluation of the model

Table 2. Performance of the Hydrological Model Based on the Weighted and Conventional Nash-Sutcliffe (NS) Efficiency Measures

	Calibration Period				Validation Period			
Gauge	NS	NS Conventional	Bias (%)	Peak Error[a] (%)	NS	NS Conventional	Bias (%)	Peak Error[a] (%)
Haltern	0.85	0.77	5.2	−11.3	0.87	0.77	1.2	−8.9
Greven	0.91	0.83	9.6	1.8	0.89	0.83	8.6	−0.6
Guntershausen	0.89	0.8	4.2	−5.1	0.87	0.8	3.7	−6.1
Marklendorf	0.92	0.86	−7.4	−7.5	0.88	0.82	−10.5	−7.1
Erfurt	0.74	0.69	10.7	11.6	0.72	0.65	11.7	−2
Wechselburg	0.83	0.74	−3.5	−7.9	0.82	0.71	−6.4	−6.6
Hundersingen	0.78	0.71	12	−5	0.75	0.68	14.5	−5.5
Donauworth	0.85	0.82	−1.2	−16.3	0.83	0.78	−2.7	−12.8

[a] Estimated as the ratio (in %) of the sum of the simulated peak flow error for observed peak flows that are greater than the minimum annual maximum observed flow and the sum of the corresponding observed peak flows.

performance, one can assume that the model captures the dynamics of the daily flow in a reasonable way in the selected catchments.

4.2. Performance of the Weather Generator

[28] As discussed in section 3.3, for the experimental setup proposed in this work, the weather generator was implemented using two approaches: stationary and nonstationary. While the daily weather variable in a given month is assumed to have the same distribution in all years in the stationary approach, the year to year variability of the distribution is accounted for in the nonstationary approach. Figure 5 shows a comparison of the monthly mean and standard deviation of the simulated and observed daily catchment average precipitation series, as well as the distributions of the corresponding annual daily maximum values for both the stationary and nonstationary simulations in the Lippe and Danube catchments, which are located in two different climate regions. Both the stationary and nonstationary simulations generally capture the monthly statistics

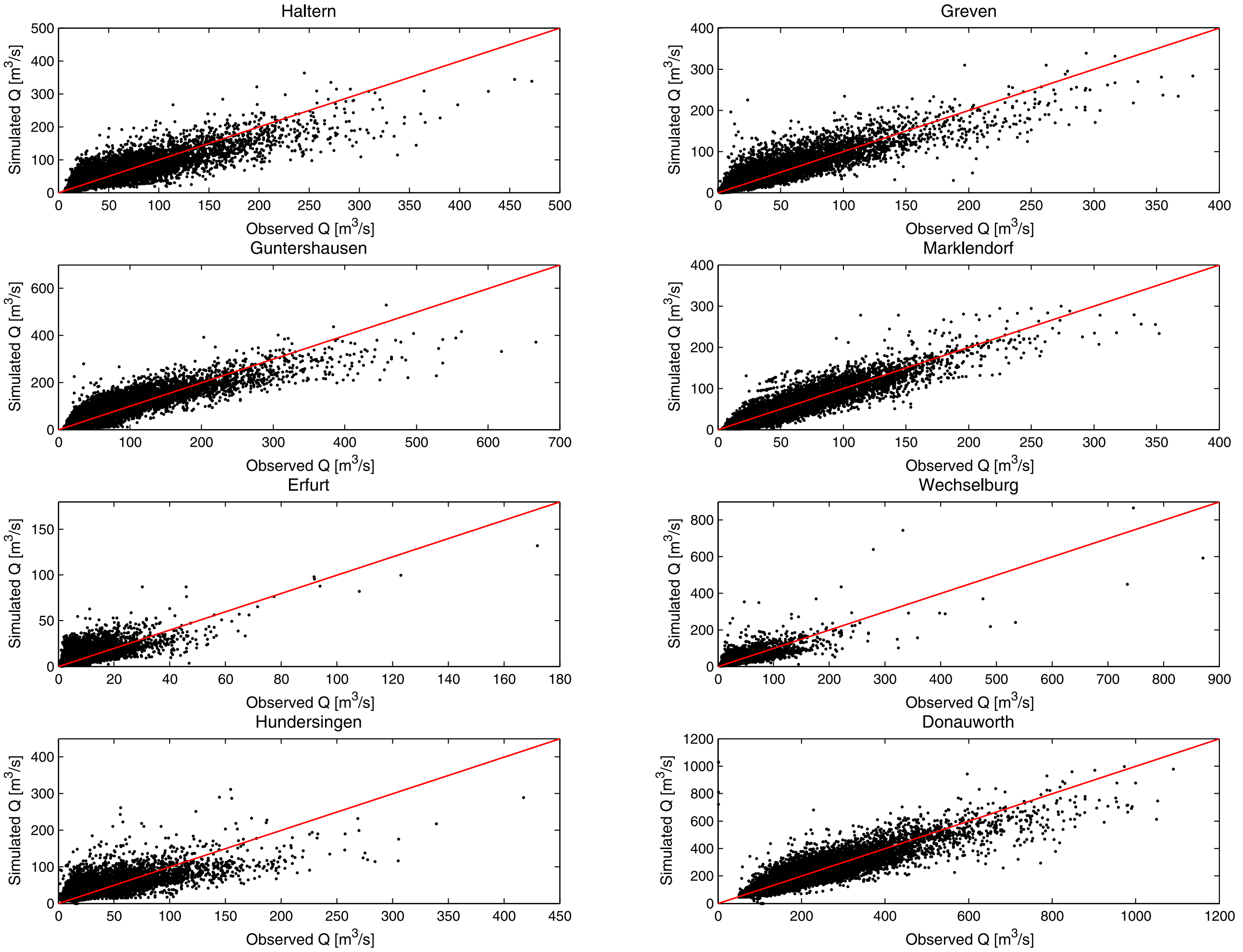

Figure 4. Scatterplots of simulated and observed daily runoff over the entire investigation period (1951–2003).

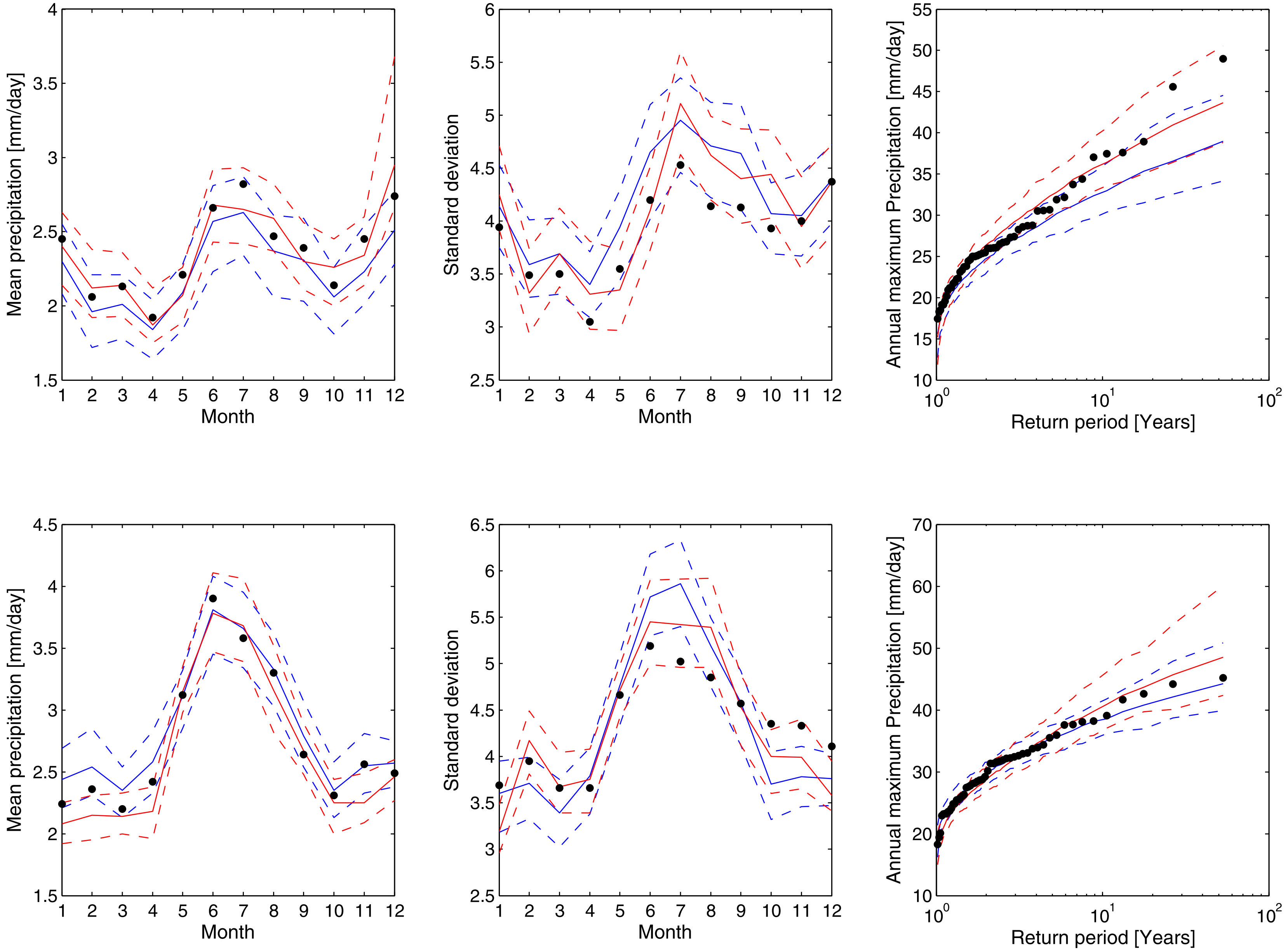

Figure 5. Monthly mean, standard deviation, and distribution of the annual maximum of observed and simulated daily precipitation for (top) Haltern and (bottom) Donauworth. Black dots represent observations, blue solid and dashed lines represent the median and 90% confidence interval (CI) of stationary simulation, respectively, and red solid and dashed lines represent median and 90% CI of nonstationary simulations, respectively.

of precipitation well as one cannot see any systematic difference between the two in simulating the mean values. The stationary simulation, however, tends to overestimate the variability of summer precipitation. Furthermore, the nonstationary simulation results in higher extremes than the stationary simulation, which often is a favorable feature as shown for the Lippe catchment. The main difference between the two simulations lies in that the nonstationary simulation tries to represent the year to year variation of the daily precipitation, as shown in Figure 6, which shows the simulated yearly variability of monthly mean precipitation in typical winter and summer months.

[29] Figure 7 also shows the monthly mean and corresponding variability of the catchment average daily maximum and minimum temperature in the two catchments. In a similar way, the temperature model also captures well the monthly mean and the corresponding variability of the daily temperature values. But, here one cannot see any systematic difference in performance between the two simulations.

4.3. Investigation of Trends in Flood Flow

[30] The rank-based Mann-Kendall test [*Kendall*, 1975], a robust, nonparametric trend test, was implemented to detect any sustained trends in the seasonal maximum flows from the investigated gauges. Test significance levels were estimated using a resampling (permutation) technique [*Good*, 1994]. Consistent with the work of *Petrow and Merz* [2009], trends are considered in this work at a 10% significance level.

[31] Table 3 shows the signs and significance levels of the trends in winter and summer maximum flows at each of the eight gauges over the period 1951–2003. At most of the stations, especially at those catchments located in the north, there is a significant trend in only one of the seasons and this tends to be winter in most cases. Trends were detected in both seasons at two of the stations, Donauworth and Erfurt, located in the south and central eastern parts, respectively. All detected trends in winter are positive and the sign of the trend in summer varies regionally. It tends to be positive in the south.

4.4. Relationship Between Trends in Flow and Meteorological Drivers

[32] The relationship between trends in meteorological variables and flood flow was investigated by (1) directly comparing changes in catchment precipitation and temperature

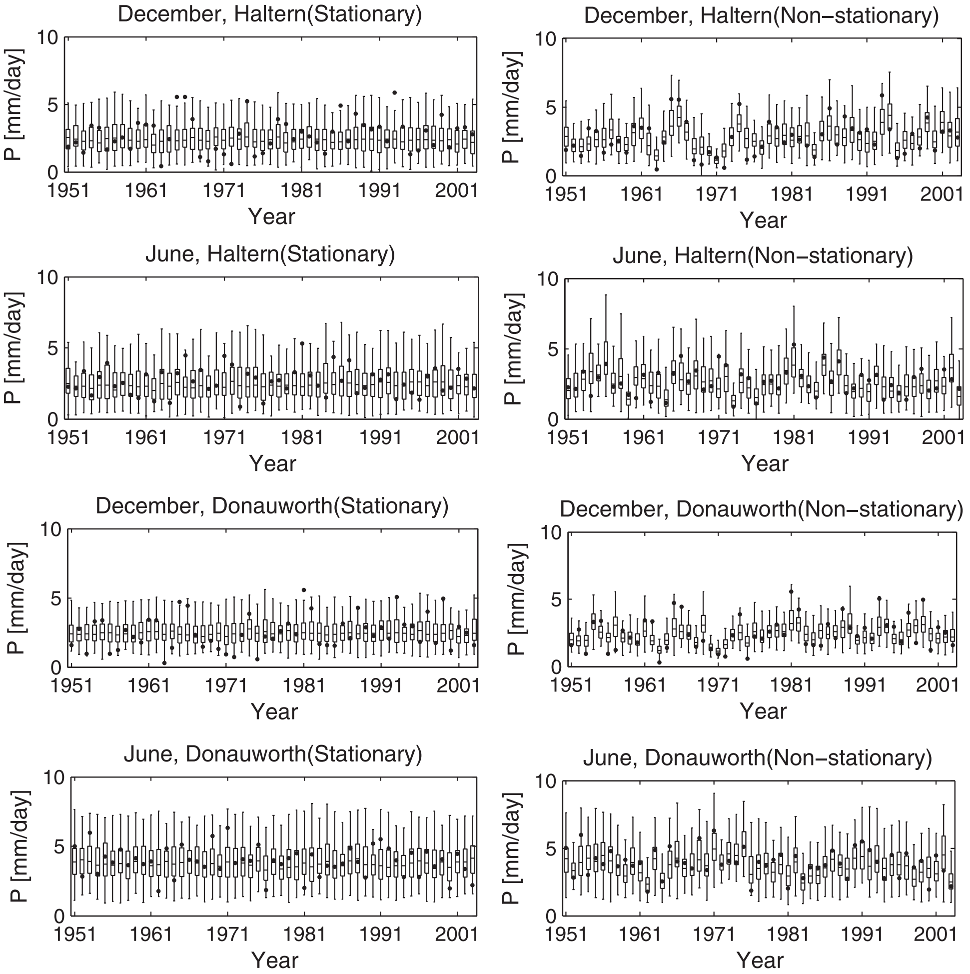

Figure 6. Yearly variation of monthly mean precipitation simulated using the stationary and nonstationary approaches in typical winter and summer months in two of the study catchments. Dots represent observations.

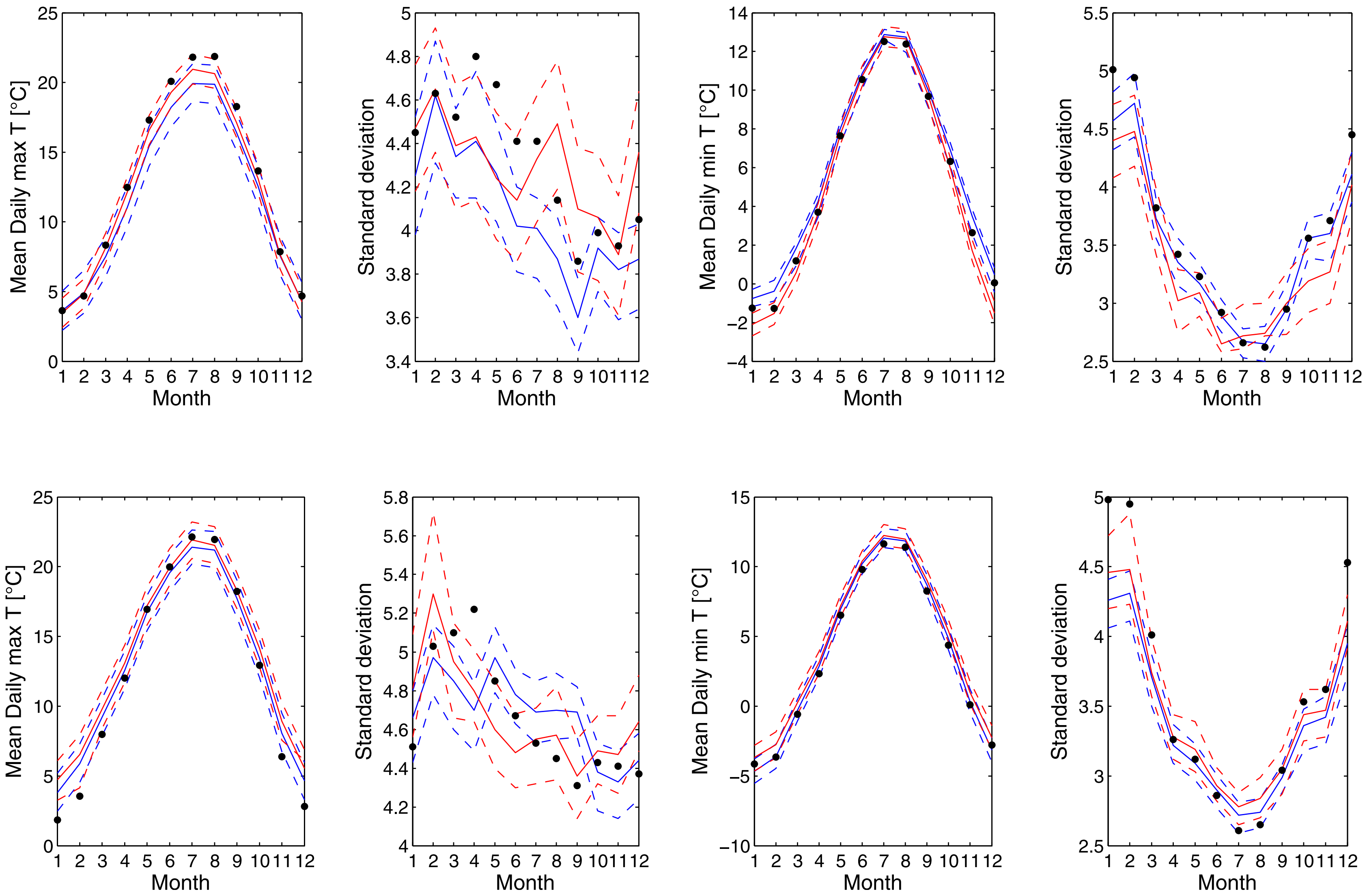

Figure 7. Monthly mean and standard deviation of daily maximum and minimum temperatures for (top) Haltern and (bottom) Donauworth. Black dots represent observations, blue solid and dashed lines represent median and 90% CI of stationary simulation, respectively, and red solid and dashed lines represent median and 90% CI of nonstationary simulations, respectively.

Table 3. Detected Trends Using the Mann-Kendall Test in the Seasonal Maximum Observed Flows and the Corresponding Catchment Average Maximum Precipitation at Different Temporal Scales[a]

			Trend Significance Level (%)							
			Winter				Summer			
Gauge	River	Regime	Q_{max}	1 Day P_{max}	3 Day P_{max}	5 Day P_{max}	Q_{max}	1 Day P_{max}	3 Day P_{max}	5 Day P_{max}
Haltern	Lippe	A	**6(+)**	**2(+)**	**6(+)**	**9(+)**	25(−)	48(+)	61(+)	78(−)
Greven	Ems	A	**1(+)**	**4(+)**	**8(+)**	**9(+)**	54(−)	13(+)	71(+)	81(+)
Guntershausen	Fulda	A	**3(+)**	29(+)	**9(+)**	19(+)	55(−)	46(−)	34(−)	40(−)
Marklendorf	Aller	B	87(+)	**10(+)**	36(+)	62(+)	**1(−)**	98(+)	43(−)	96(−)
Erfurt	Gera	B	**2(+)**	**2(+)**	**2(+)**	**7(+)**	**5(−)**	93(+)	72(+)	42(−)
Wechselburg	Zwickauer Mulde	B	**6(+)**	**3(+)**	36(+)	39(+)	30(−)	60(+)	83(−)	35(−)
Hundersingen	Danube	B	36(+)	**10(+)**	**4(+)**	**10(+)**	**5(+)**	19(+)	45(+)	15(+)
Donauworth	Danube	C	**9(+)**	25(+)	18(+)	20(+)	**1(+)**	14(+)	**1(+)**	**4(+)**

[a] Trends significant at the 10% level are indicated in bold. Plus and minus in parentheses indicate positive and negative trends.

with that of the flood, and (2) applying the model-based methodology introduced in section 3.3. Three implementations of the weather generator were considered to evaluate the effects of changes in the different components of the meteorological variables on the seasonal extreme flows. For each implementation, an ensemble of 100 realizations of daily weather variables was generated for the period 1951–2003, which is the same period as the period over which trends in the seasonal maximum flows were computed. The generated variables were then interpolated to the centroids of the subcatchments draining to each gauge using ordinary kriging. The hydrological model was then driven by the weather variables thus interpolated and the seasonal maximum flows corresponding to each realization were computed.

4.4.1. Direct Comparison of Changes in Precipitation and Flow

[33] For the catchments and seasons with detected trend in the seasonal maximum flows, we directly compared the trends with the corresponding trends in the seasonal maximum of daily precipitation aggregated over windows of different lengths. The values of seasonal maximum of catchment average values of 1, 3, and 5 days total precipitation were investigated. A similar comparison was carried out with trends in catchment average seasonal mean of maximum, mean, and minimum daily temperatures. Furthermore, trends in the number of days with catchment average daily mean temperature less than 0°C, which controls the snow accumulation and melt mechanisms, were compared. The significance level of all trends was estimated using the Mann–Kendall test and similar to the extreme flows, trends are considered significant at 10% level.

[34] The signs and the significance levels of the trends in the seasonal maximum of the catchment average precipitation at the investigated temporal scales are shown in Table 3. They indicate that for catchments in the north and central part, where winter maximum flow has shown increasing trend, the corresponding seasonal maximum of 1 day total catchment average precipitation also showed significant increase. At Guntershausen, however, no significant trend was detected in the maximum 1 day total precipitation. Instead, the maximum 3 day total showed a significant increase. Although a strong upward trend was detected in the winter maximum flow at Donauworth, located in the south, no corresponding trend was detected in the maximum catchment average precipitation at all investigated temporal scales. In most of the catchments where summer maximum flow showed significant trend, no corresponding changes were detected in the catchment average maximum precipitation at all investigated temporal scales. At Donauworth, however, the maximum of the aggregated 3 and 5 day total showed significant increasing trend.

[35] Although the precipitation extremes at a temporal scale approximately equal to the estimated catchment concentration time showed significant changes that correspond to the changes in extreme flows in some catchments, there are some instances where this is not the case (See Tables 1 and 3 at Marklendorf, Hundersingen, Donauworth and Erfurt). Further analysis was done to investigate the correlation between the extreme seasonal flows and the precipitation total aggregated over several days just before the event. Table 4 shows the number of days before the event over which the aggregated precipitation shows a maximum correlation, together with the corresponding correlation coefficient and the significance level of the trend in the aggregated precipitation estimated using the Mann–Kendall test. One can see from the table that the number of days varies seasonally and it appears to be higher than the estimated catchment time of concentration. The trends in the aggregated precipitation are also not significant in most of the catchments. The result suggests that the extreme flows may not necessarily have been caused by the catchment average extreme precipitation at a temporal scale corresponding to the catchment concentration time.

[36] Table 5 also shows the significance level of the trends in the temperature related variables in comparison with that of seasonal maximum flows. In all catchments, there is a clear evidence of increasing trend in both the minimum and maximum daily temperatures. Correspondingly, there is a decline in the number of days with the daily mean temperature below freezing point.

[37] The above comparison shows that there is no general correspondence between trends in extreme flows and extreme catchment average precipitation. This lack of correspondence is further shown in Figure 2, which shows comparison of the relative frequencies of extreme flows and extreme catchment average precipitation for each month. One can see from Figure 2 that the relative frequencies of the two do not generally display similar monthly variation, which means that the extreme flows and extreme

Table 4. Antecedent Days Corresponding to Maximum Correlation Between Aggregated Precipitation and Seasonal Maximum Flows and Significance Levels of the Trends in the Aggregated Precipitation[a]

Catchment	Season	Day of Maximum Correlation	Correlation Coefficient	Trend Significance Level (%)	Estimate of Travel Time (Days)
Haltern	winter	7	0.423	**2(+)**	2.84
	summer	12	0.8	67(−)	2.84
Greven	winter	7	0.49	**1(+)**	3.12
	summer	12	0.8	88(−)	3.12
Guntershausen	winter	13	0.4	**8(+)**	2.7
	summer	23	0.84	23(−)	2.7
Marklendorf	winter	8	0.53	**1(+)**	3.88
	summer	18	0.69	67(−)	3.88
Erfurt	winter	3	0.48	36(+)	0.6
	summer	6	0.63	30(−)	0.6
Wechselburg	winter	5	0.2	54(+)	1.4
	summer	10	0.84	31(−)	1.4
Hundersingen	winter	5	0.72	93(+)	1.64
	summer	6	0.88	87(+)	1.64
Donauworth	winter	5	0.514	79(+)	4.09
	summer	4	0.68	**7(+)**	4.09

[a]Trends significant at the 10% level are indicated in bold. Plus and minus in parentheses indicate positive and negative trends.

precipitation may not temporally coincide. This leads to the conclusion that the extreme flows are not necessarily caused by extreme catchment scale precipitation. Some of the events may have been caused by locally extreme precipitation but which cannot be regarded as extreme at a catchment scale. They could have even been caused predominantly by snow melt with no or little precipitation. Furthermore, interpretation of the implications of the detected trends in the temperature variables based only on a statistical analysis is not straightforward since their effect could depend on their interaction with precipitation. Therefore, there is a need for analysis that takes into consideration the effect of the possible spatial variability of the precipitation extremes and the interactions between precipitation and temperature.

[38] A test for the presence of step change has also been carried out on the seasonal maximum flows using the rank-based Wilcoxon-Mann-Whitney test. The result shows a significant upward shift in the winter maximum flows at Greven and Donauworth in the year 1978. Similar analysis was carried out on the corresponding seasonal catchment average maximum precipitation of different duration (1–5 days), and catchment average mean maximum and minimum temperatures to see if there is any parallel change in the meteorological drivers. At Greven, the catchment average 1 day precipitation shows a significant upward shift in the year 1984 while the 3 and 5 day maximum show a similar significant shift in 1980. On the other hand, the catchment average maximum precipitation at Donauworth did not show any step change at all durations. The catchment average daily maximum and minimum temperatures in both catchments showed a positive shift in the year 1988.

[39] On the basis of the above comparison, it is difficult to attribute the step change in the extreme flows at the two gauges to the meteorological drivers since the changes did not show any temporal correspondence. Nevertheless, one cannot rule out the possibility since the different meteorological variables can have interaction that could lead to a change that cannot be discerned through a separate statistical analysis of the individual meteorological variables. The changes could also have been caused by nonmeteorological factors, such as land use and land management changes. However, we cannot confirm this since detailed information on land use changes is not available to us.

4.4.2. Stationary Weather Variables

[40] As discussed in section 1, we propose to attribute changes in flood behavior to meteorology by employing a multisite stochastic weather generator to generate ensembles of synthetic meteorological variables and driving a hydrological model with them. Figure 8 shows the year to year variation of the ensemble of seasonal maximum flows simulated with stationary synthetic meteorological variables

Table 5. Detected Trends Using the Mann-Kendall Test in the Seasonal Catchment Average Indices of Daily Temperature[a]

	Trend Significance Level (%)							
	Winter				Summer			
Gauge	T_{max}	T_{min}	T_{mean}	$T_{mean} < 0$ days	T_{max}	T_{min}	T_{mean}	Tmean < 0 days
Haltern	1(+)	2(+)	2(+)	5(−)	1(+)	1(+)	1(+)	–
Greven	1(+)	1(+)	2(+)	6(−)	1(+)	1(+)	1(+)	–
Guntershausen	2(+)	2(+)	2(+)	8(−)	1(+)	1(+)	1(+)	–
Marklendorf	2(+)	2(+)	5(+)	10(−)	1(+)	1(+)	1(+)	–
Erfurt	3(+)	2(+)	2(+)	3(−)	3(+)	1(+)	1(+)	–
Wechselburg	1(+)	1(+)	1(+)	3(−)	1(+)	1(+)	1(+)	–
Hundersingen	1(+)	1(+)	2(+)	3(−)	1(+)	1(+)	1(+)	–
Donauworth	1(+)	1(+)	1(+)	2(−)	1(+)	1(+)	1(+)	–

[a]All trends are significant at the 10% level. Plus and minus in parentheses indicate positive and negative trends.

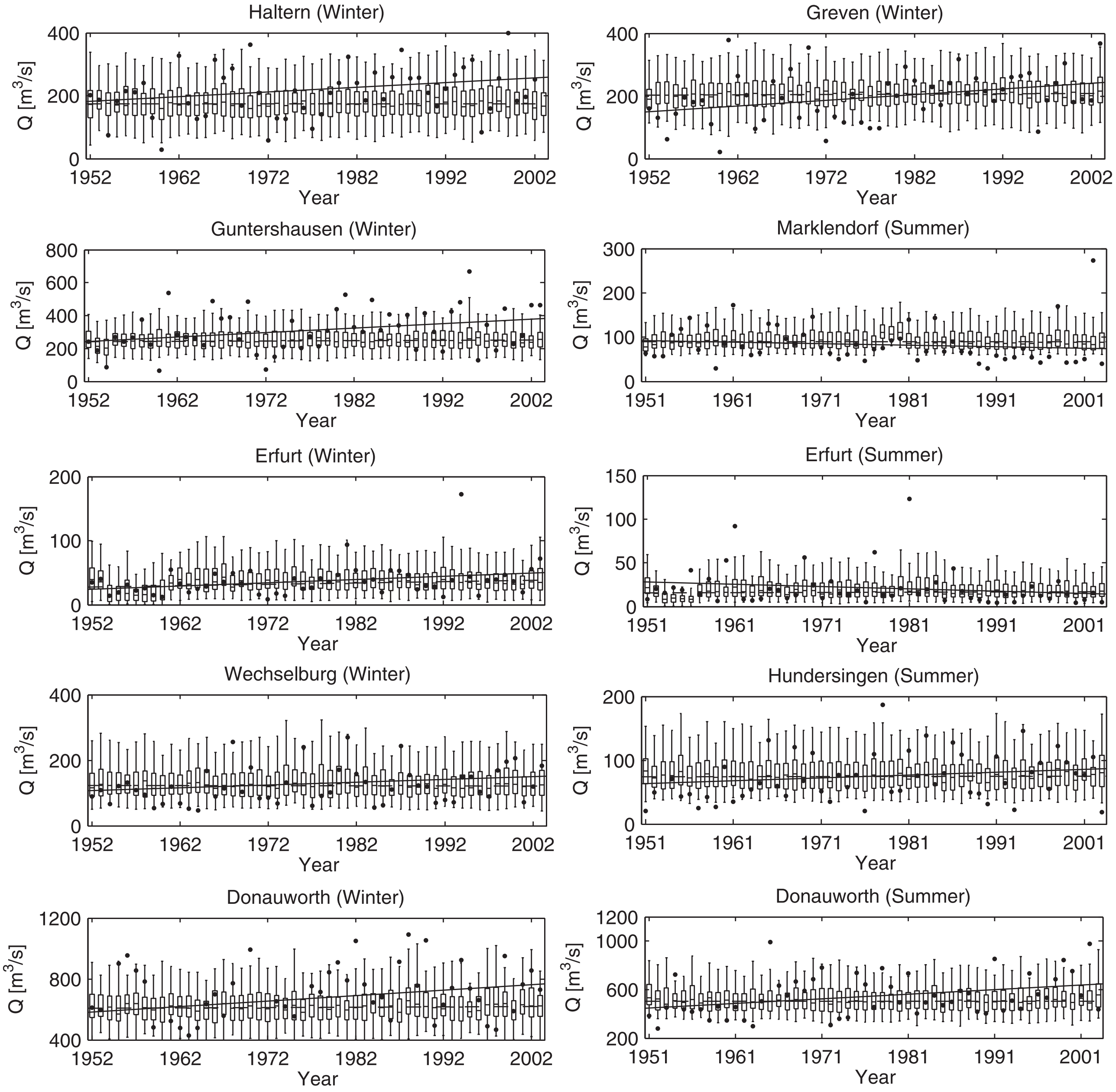

Figure 8. Variability of the seasonal maximum flows simulated with ensembles of stationary weather variables shown as box plots. Dots are observed values, solid lines correspond to the trend lines of observed maxima, and dashed lines are trend lines of the median simulated maxima.

at each station, shown as a box plot for each year. Figure 8 shows only seasons in which trends in the observed maximum flows were detected at each gauge. The corresponding observed values are also superimposed to show how they compare with the simulations. One can see from Figure 8 that the simulated median maximum flows at all gauges are nearly constant over the entire simulation period and the trends exhibited by the observations are totally destroyed. This is further shown in Figure 9, which shows the nonparametric pdf of the Mann–Kendall test statistic of the seasonal maximum flows simulated using the 100 simulations of the meteorological drivers, which is fitted using kernel smoothing. This shows that the model produces a stationary flood time series when driven by a stationary climate driver and does not produce a trend that is caused by changes in nonclimate driving.

4.4.3. Nonstationary Precipitation and Stationary Temperature

[41] Daily synthetic precipitation series were generated from distributions that vary from year to year while the temperature and radiation series were generated from stationary distributions. Such an analysis reveals whether the historical change in the distribution of precipitation alone would have resulted in a trend in the extreme flow. While the simulated trends are of the same direction as those of the observations and are also significant in most of the catchments, suggesting that changes in precipitation alone

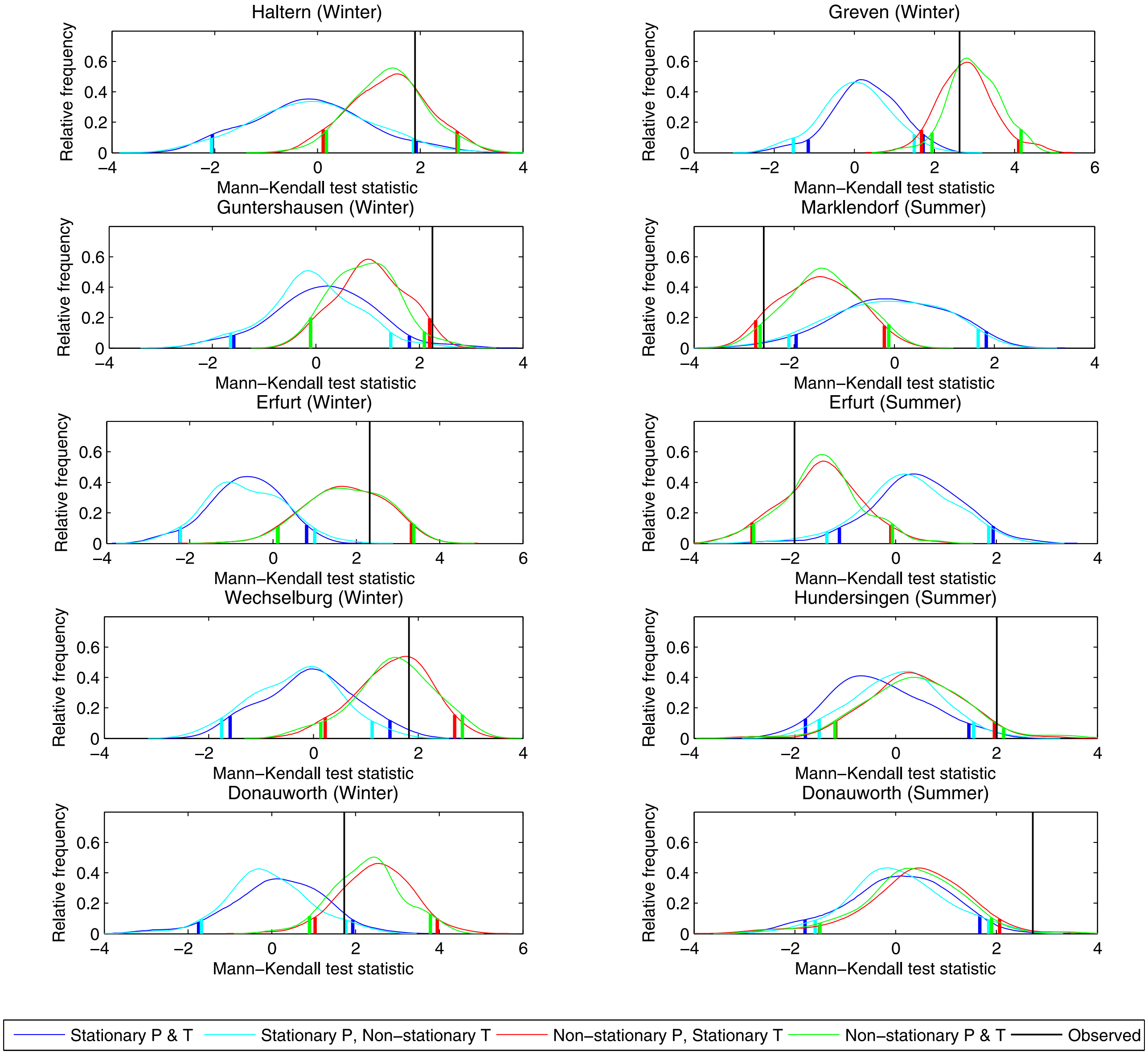

Figure 9. Frequency distributions of the Mann-Kendall test statistics of simulated seasonal maximum flows with the 90% confidence intervals for the different experiments together with that of the corresponding observed extreme flows.

would have caused trends similar to that of the observed, simulated trends in the summer maximum flows in the south (Hundersingen, Donauworth) and winter maximum at one of the catchments in the north (Guntershausen) are not significant (Table 6 and Figure 9). This suggests that the observed trends in these catchments have possibly been caused by other factors than a change in precipitation alone.

4.4.4. Stationary Precipitation and Nonstationary Temperature

[42] This analysis is carried out by keeping the distribution of precipitation stationary while simulating temperature and radiation from distributions that vary from year to year. From Table 6 and Figure 9, it can be seen that no significant trend was detected in the extreme flows in any of the catchments. The results indicate that the observed changes in temperature and radiation would not have caused any significant change in the maximum flow in all catchments.

4.4.5. Nonstationary Weather

[43] With this analysis, one can analyze the combined effect of the evolution of all the meteorological variables on the seasonal maximum flows. All the variables were generated from distributions that vary from year to year. Figure 10 shows comparison of the simulated seasonal maximum flows with the corresponding observations. As shown in Table 6 and Figure 9, the trends of the seasonal maximum flows are very similar to the case where only the precipitation changes while the other variables are kept stationary. Both the direction and the significance of the changes in the seasonal maximum flows are consistent with the observed changes in most catchments, suggesting that

Table 6. Trends Estimated Using the Mann-Kendall Test in the Simulated Seasonal Maximum Flows When the Hydrological Model is Driven by Different Combinations of Precipitation (P) and Temperature (T) in Terms of the Variability of Their Distribution[a]

Gauge	Size (km^2)	Number of Meteorological Stations Used	Season	Trend: Significance Level (%)				
				Observed	Stationary P, Stationary T	Nonstationary P, Stationary T	Stationary P, Nonstationary T	Nonstationary P, Nonstationary T
Haltern	4273	91	winter	**6 (+)**	88(−)	**8(+)**	92 (−)	**6(+)**
Greven	2842	59	winter	**1(+)**	72(+)	**1(+)**	96(+)	**1(+)**
Guntershausen	6366	149	winter	**3(+)**	85(+)	14(+)	94(−)	16(+)
Marklendorf	7209	100	summer	**1(−)**	97(−)	**5(−)**	94(−)	**6(−)**
Erfurt	843	21	winter	**2(+)**	48(−)	**8(+)**	52(−)	**8(+)**
Erfurt	843	21	summer	**5(−)**	62(+)	**7(−)**	76(+)	**7(−)**
Wechselburg	2107	39	winter	**6(+)**	95(−)	**6(+)**	75(−)	**8(+)**
Hundersingen	2639	67	summer	**5(+)**	71(−)	68(+)	95(+)	69(+)
Donauworth	15,037	217	winter	**9(+)**	85(+)	**2(+)**	91(−)	**2(+)**
Donauworth	15,037	217	summer	**1(+)**	92(+)	99(+)	60(+)	69(+)

[a] Trends significant at the 10% level are indicated in bold. Plus and minus in parentheses indicate positive and negative trends.

change in meteorological drivers is behind the detected changes in the extreme flows. The summer trends in the two southern catchments (Hundersingen, Donauworth) and the winter trend in one of the northern catchments (Guntershausen) are not significant, although the directions of the trends are the same. This suggests that there are possibly nonweather-related causes for the detected observed changes in the extreme flows in these catchments.

[44] A test for step change has also been carried out to the simulated seasonal maximum flows of all the four experimental setups using the Wilcoxon-Mann-Whitney test. In the setups where precipitation was kept stationary, only a few of the ensemble members showed significant step change, each of them at different times. In the setups where variability of precipitation was introduced, 31% of the ensemble members of the winter maximum flows at Greven showed an upward step change between 1978 and 1984. In all the other catchments, only a few members showed significant changes. This suggests that the step changes detected in the observed extreme winter flows at Greven and Donauworth cannot be explained by the changes in the meteorological variables.

5. Discussion

[45] The results shown in sections 4.1–4.4 demonstrate the problems associated with investigating changes in the extreme catchment average precipitation and comparing them with the changes in the corresponding extreme runoff to attribute the changes in the flow to changes in precipitation. This is especially the case as the size of the catchment increases, as shown in the comparison of the corresponding winter trends in the largest investigated catchment (gauge Donauworth). The absence of trends in the maximum catchment average precipitation at any of the investigated temporal scales would prompt one to conclude that the detected trend in the maximum flow could possibly be attributed to a nonprecipitation related driver. However, since nonstationarities in the nonclimate attributes are not included in the present study framework, whether nonclimate effects are behind the detected trend cannot be inferred. The modeling result indicates a significant trend in the maximum flow consistent with that of the observed flow when the model is driven by ensembles of precipitation series in which the temporal dynamics of the distribution of precipitation and its variability at a finer spatial scale are implicitly reproduced. On the other hand, the model result clearly shows the absence of any trend in the maximum flow when the model is driven by precipitation series where the temporal variability of the distribution is removed while the spatial variability is kept. Provided that the assumptions discussed in section 3.4 on the implementation of the hydrological model hold, these results provide enough evidence to conclude that the observed trend in the maximum flow is at least partly attributable to the change in the distribution of precipitation.

[46] The flow resulting from a precipitation event depends not only on the magnitude of catchment scale precipitation, but also on the characteristics of the event and the antecedent conditions in the catchment. Even though there were no change in the catchment scale extreme precipitation, changes in the characteristics of the precipitation would lead to a change in the resulting extreme flow. For instance, a change in the temporal and spatial clustering of precipitation events may favor formation of extreme flow depending on how the events are spatially clustered and how they evolve temporally. Also, changes in precipitation extremes that have taken place in localized spatial extents, either at a single area or different spatial locations may not lead to a change in the catchment scale extreme precipitation, depending on the spatial pattern of the events. They may, however, result in a significant change in the response at the catchment outlet.

[47] Another important attribute of precipitation in relation to extreme flows is its temporal scale. The time needed for the entire catchment to contribute to the flow at the catchment outlet depends on the size and other morphological characteristics, as well as the antecedent moisture state of the catchment. Therefore, even if one tried to associate changes in extreme flows with changes in the extremes of catchment average precipitation, one would need to know beforehand at what temporal scale the precipitation amounts need to be computed—a task which is not obvious as some of the factors, such as the initial catchment state, are variable from event to event.

[48] The problems discussed in the previous paragraphs in relation to associating observed trends in extreme runoff with that of observed precipitation get even more complicated

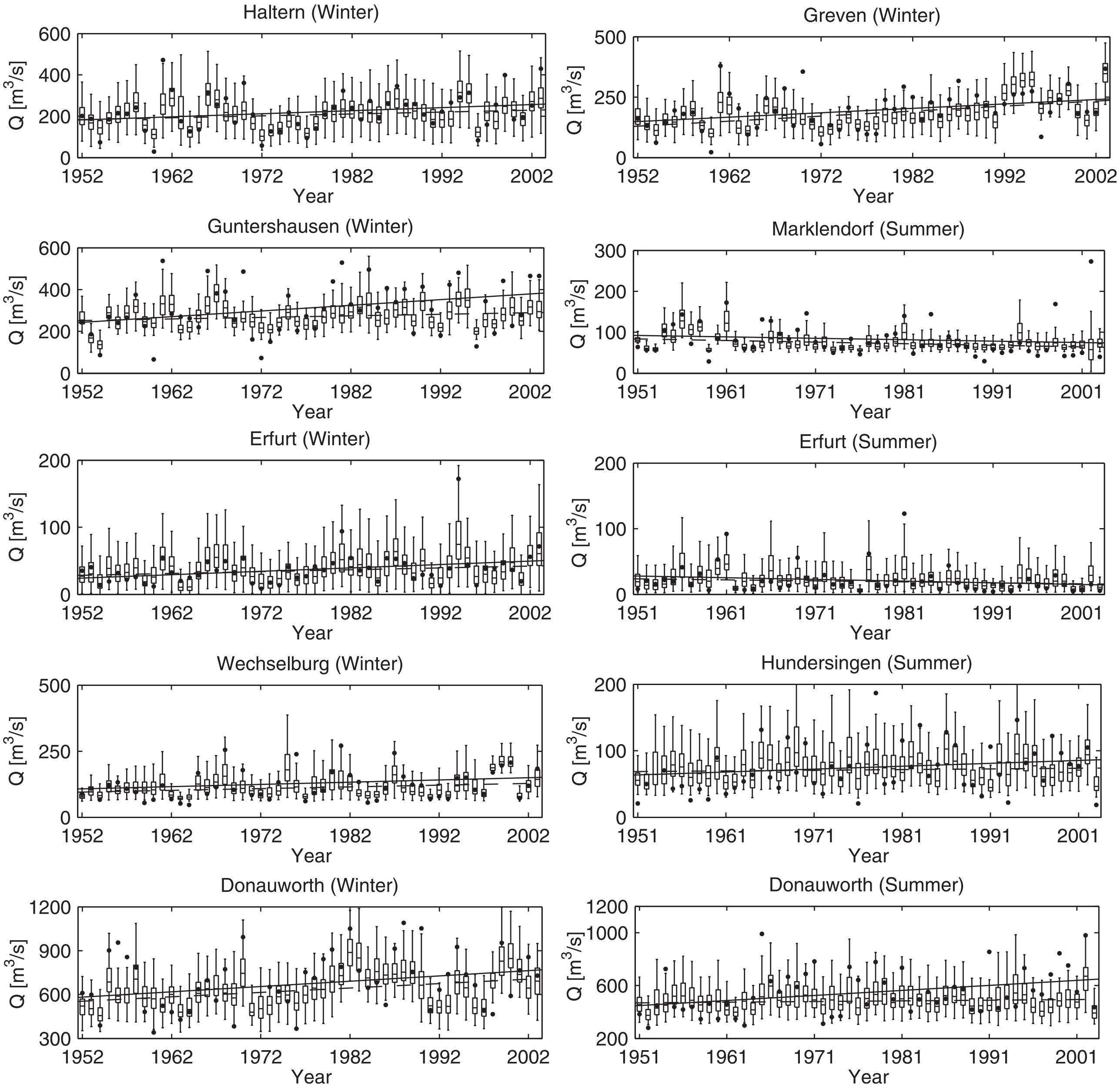

Figure 10. Same as Figure 8, but simulated with nonstationary precipitation and temperature.

when precipitation is falling at different locations at different times as the catchment response depends on how the contributions from the different events in spatially different locations sum up. The method implemented here, however, takes all such aspects implicitly into consideration and avoids the need to identify the appropriate temporal and spatial scales of precipitation that need to be analyzed to associate the changes in the flow with that of precipitation. The possible effect of the variability of subdaily precipitation, especially in small catchments, is not however considered in setup of the methodology.

[49] Temperature has been found to be less important in explaining the detected trends in all the investigated catchments. Temperature generally affects extreme flows in two ways. First, through evapotranspiration, it can affect the initial soil moisture state of the catchment before precipitation events that could cause extreme flows. For winter events, this is less important in our study regions since the rate of evapotranspiration is generally low in winter. It could have a significant effect in summer extreme flows. To investigate whether the temperature variability has caused an increase in summer evapotranspiration loss, we computed the trend in the difference of the total seasonal flows simulated under nonstationary and stationary temperature over the investigation period. The result shows that although there is a general tendency of decline of the summer flows, the trend is significant at 10% only at Donauworth and Hundersingen. However, our modeling result shows that the change in temperature has not resulted in a significant change in the extreme summer flows in these catchments,

suggesting possibly a less significant effect of evapotranspiration on extreme flows than on total flows over a longer period.

[50] The degree to which evapotranspiration plays a role also depends on the type of vegetation cover. The vegetation cover was kept stationary in the study and any possible variation in agriculturally used areas is not accounted for. This might have an impact on the trends in summer extreme flows simulated to investigate the impact of variation of temperature.

[51] The second way in which temperature affects extreme flows is through altering the snow accumulation and melt dynamics. This is generally reflected either as a shift in timing or a change in the magnitude of extreme flow due to a rapid or slow melt of the snow pack or both. This in turn depends on the cumulative amount of precipitation on days below freezing temperature and the timing and the magnitude of the temperature above the freezing point once snow is accumulated. It would be possible to explicitly investigate the link between snow processes and flood flows locally by deriving snow cover and depth from observations and simulation. However, one would face a similar problem discussed in relation to the observed precipitation, since the process is generally spatially and temporally variable. In the method proposed here we are, nevertheless, looking at the overall effect of the change in the distribution of temperature on the flow at a catchment scale. The overall snow mechanism is assumed to be represented in a spatially consistent way by the experimental setup of this work, since the distribution of the daily temperature in the weather generator is conditioned on the precipitation state and both the spatial and autocorrelations of both variables are also represented. Nevertheless, this needs to be verified with measured snow depth information.

[52] In order to investigate the effect of the snow accumulation and melt mechanism on the change in extreme flows, a trend test was carried out on the total catchment average amount of snow falling in winter for each of the experimental setups. The result shows that there is a significant (10%) decline in the amount in all the investigated catchments when the year to year variability of temperature is introduced. No significant change was detected when the temperature variability was kept stationary. A similar test conducted on the timing of the seasonal peak flow showed no significant trend in all catchments over the investigation period.

[53] The test result mentioned above should be interpreted separately for each catchment in the context of the runoff regime of the catchment. The catchments in the flood regime zone A, which all showed increasing trend in their winter extreme flows, have a pluvial runoff regime and snow has little effect on their runoff generation. Any snow formed melts away immediately and does not accumulate over a longer period to cause flooding that could result from snow melt. As winter evapotranspiration loss in the region is little, the overall effect of temperature on the extreme flow is therefore negligible, as the results demonstrate.

[54] The other catchments have a runoff regime that is partly influenced by snow accumulation and melt. In the mountainous parts of the catchments of regimes B and C, snow accumulates during winter and contributes to the runoff in spring and in regime C even in summer. The decline in the accumulated snow would mean that there will be less contribution from snow melt to the high flows. However, snow melt is not the sole contributor of the extreme flow and the contribution of rainfall to the runoff could outweigh that of snow melt. This is further confirmed by the absence of any trend in the timing of the peak flow, which otherwise would have shifted to earlier time because of a faster snowmelt that ensues earlier because of increased temperature.

[55] The absence of any significant trend in the simulated extreme summer flows at Donauworth and Hundersingen using all combinations of changes in the meteorological drivers, while the observed extreme flows show a significant increasing trend, suggests that none of the meteorological drivers are associated with the detected trend in the flows. Therefore, on the basis of the analysis, we conclude that nonmeteorological factors, possibly land management, are behind the changes. The catchment draining to Hundersingen is nested in the bigger catchment draining to Donauworth and this can be used as additional confirmation to our speculation. Nevertheless, one should not rule out the uncertainty in each component of the chain of models on the results. Although part of the uncertainty that can be attributed to the variability of the meteorological drivers has been taken into account by employing ensembles of synthetic meteorological drivers, the uncertainty associated with the hydrological model is still there. Also, as discussed earlier in this section, the lack of accounting for a possible variation of the vegetation cover could have an impact on evapotranspiration in summer, which could potentially affect the resulting trend in the simulated summer extreme flows.

6. Conclusions

[56] A method for the attribution of the change in extreme river flow to meteorological drivers has been proposed and tested on seasonal floods from mesoscale catchments of different sizes in different parts of Germany. The proposed method uses a hydrological model to simulate the dynamics of the river flow with the full range of variability of the meteorological drivers, both spatially and temporally. The observed meteorological time series are just a single realization of the underlying distributions. By synthesizing ensembles of the meteorological drivers through implementation of a weather generator that preserves the statistical distributions of the different meteorological variables, including the interactions between the variables both in space and time, one can account for the possible uncertainty in the estimation of the change in the flow that arises from its estimation from a single realization. Furthermore, the results have demonstrated that it is possible to assess the relative importance of the different components of the meteorological drivers in accounting for the change detected in the flow. To this end, only the distribution of one of the variables is varied with time while keeping the others temporally stationary.

[57] On the basis of implementation of the approach in eight German catchments, precipitation has been found to be the major meteorological driver of the detected changes in the seasonal extreme flows in most of the investigated catchments. Temperature related changes are found to be

invariably less important in explaining the observed changes in all catchments.

[58] It has been shown that the proposed method is able to detect changes in extreme flows that are caused by changes in the distribution of precipitation by approaching the problem in a different way than the traditional approach of attribution, which compares the trend in the extreme flow with the corresponding change in extreme catchment scale meteorological variable, such as precipitation. The traditional approach does not allow investigation of the impact of the spatial and temporal variability of the meteorological events that could have impact on the annual or seasonal extreme flows unless the events are the corresponding annual or seasonal extreme events. The flow generated by a precipitation event, however, depends on the characteristics of the event, such as its storminess and the direction of the storm movement and also the initial catchment state. The direct comparison method does not take these into consideration. Furthermore, the annual or seasonal extreme precipitation could be in snow form, which may not have an immediate impact on the flow. On the other hand, the annual or seasonal extreme flow could be generated by melt of accumulated snow with no precipitation recorded during the event. The proposed approach takes these issues implicitly into account. This allows, for instance, identifying whether a nonsignificant change in precipitation at a given temporal and spatial scale could possibly cause a significant change in the extreme flow.

[59] The approach followed in the present work makes use of a hydrological model calibrated by setting the nonclimate catchment attributes stationary under the assumption that the model calibrated in this way can be used as a reference model to investigate whether changes in the distributions of the meteorological drivers are translated into a significant trend in the simulated runoff. Ignoring the nonstationarities makes it impossible to fully attribute the changes in the runoff. Future work should investigate the effect of such nonstationarities on the changes in the runoff as well as how they affect the assumption of using the model calibrated under stationary nonclimate factors to decipher changes in streamflow resulting from changes in the climate drivers. Furthermore, as the proposed approach is based on implementation of a chain of models, it should be noted that each component of the chain introduces uncertainties. No uncertainty study was carried out on the hydrological model. A single set of optimum parameters, estimated through model calibration against observed daily discharge data, was employed. Future work should investigate the hydrological model uncertainty on the results.

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