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Changes in Saxon Precipitation Characteristics

Trends of Extreme Precipitation and Drought




Cuvillier Verlag Göttingen
Internationaler wissenschaftlicher Fachverlag

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Von der Fakultät für Geowissenschaften, Geotechnik und Bergbau
der Technischen Universität Bergakademie
genehmigte

DISSERTATION

zur Erlangung des akademischen Grades
doctor rerum naturalium
Dr. rer. nat.
vorgelegt

von Dr. Stephanie Hänsel

geboren am 25. 10. 1978 in Riesa

Gutachter: Prof. Dr. Jörg Matschullat, Freiberg
Prof. Dr. Christian Bernhofer, Tharandt
Prof. Dr. Uwe Ulbrich, Berlin

Tag der Verleihung: 16. Dezember 2008

Bibliografische Information der Deutschen Nationalbibliothek
Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.ddb.de abrufbar.
1. Aufl. - Göttingen : Cuvillier, 2009
Zugl.: (TU) Freiberg, Univ. Diss., 2009

978-3-86955-154-8

Nonnenstieg 8, 37075 Göttingen
Telefon: 0551-54724-0
Telefax: 0551-54724-21
www.cuvillier.de

1. Auflage, 2009
Gedruckt auf säurefreiem Papier

978-3-86955-154-8

Contents

1 Introduction

Climate is not a constant but rather variable in our earth's history. This climate variability refers to variations in the mean state and other statistics of the climate on all spatial and temporal scales beyond that of individual weather events (IPCC 2007). Besides major oscillations like those between glacial and interglacial periods, shorter scale variations appear like the Medieval Warm Period, the Little Ice Age or the recent global warming.

Rising temperatures and changing precipitation pattern over Central Europe within the last century have lead to discussions about changes in the frequency and intensity of heavy precipitation and drought events. The study of such extreme events is of particular interest, because human society and ecosystems are especially vulnerable to those phenomena, as various examples over recent years have shown. Furthermore, changes in the extremes of the precipitation distribution may be surprisingly high for seemingly modest mean changes. Physically, the rising temperatures are expected to be associated with an intensification of the global water cycle – more frequent and intense heavy precipitation events are possible. Naturally occurring droughts may be aggravated by increased evapotranspiration. Thereby, precipitation changes are generally more spatially and seasonally variable than temperature changes (IPCC 2007). Different regional developments are possible (Schönwiese and Rapp 1997), as the effects of a global warming may be intensified, compensated or overcompensated by altered weather conditions (Fricke 2003). Scientifically, the processes that locally alter precipitation are not well understood (Trenberth 1999).

This study analyses changes of regional precipitation characteristics within the last century in the German Free State Saxony and its surroundings with emphasis on the extremes, notably heavy precipitation and drought. The results are discussed in the context of global and regional climate changes. Some analysis use regional data besides calculating station trends. For this purpose the stations are grouped into nine regions with similar natural landscapes and precipitation characteristics.

The study area is situated at the interface of dominantly oceanic versus continental climate regimes. Therefore, it shows precipitation characteristics and trends that are considerably different from the western parts of Germany, where the annual precipitation totals increased by just under 10% from 1901 to 2000 (Schönwiese and Janoschitz 2005). In Saxony the annual precipitation totals showed indifferent trends during the last 50 years (Franke et al. 2004; Hänsel et al. 2005); probably related to the increasing continentality of the climate. They do show, however, a distinct redistribution of rainfall during the year with drier summer half years and wetter winter half years, as Schönwiese and Rapp (1997) noted for Germany.

Analysing extreme climate events is associated with some challenges. The first one is connected to their definition – no universal definition of drought or heavy precipitation exists. The definitions highly depend on the application area and sector. The IPCC (2007) states some general definition of an extreme weather event: "*An extreme weather event is an event that is rare at a particular place and time of year*", but "*definitions of rare vary*". The second challenge relates to the significance and robustness of statistical analysis. Detecting significant changes in the available instrumental weather records is difficult, due to the rarity of extreme events. Thus, long time series and special statistical methods are needed (Gerstengarbe and Werner 1993). If no homogenous long time series of daily precipitation totals exist, analysis should concentrate on changes in moderately extreme events yielding enough events for reliable statistical analysis.

Although this study focuses first on changes in drought and wet extreme characteristics and patterns, initially some basic analysis of average precipitation changes is done. The precipitation shift from the summer to the winter months is quantified and an analysis concerning the precipitation classes with major changes is performed. A trend comparison of different time intervals allows qualifying the temporal representativeness of trends.

Drought is considered by many to be the most complex but least understood of all natural hazards affecting more people than any other natural hazard (Hagman 1984). It arises from a natural decline in precipitation over an extended period of time, although other climate factors may significantly aggravate the severity of a drought event (Wilhite 2000). In Central Europe, drought is often underestimated, because its impacts are less obvious and spread over larger geographical areas than damages resulting from other natural hazards. In contrast to floods, droughts seldom result in structural damage. Therefore, the quantification of their impacts is a far more difficult task. Droughts basically differ in three basic characteristics: intensity, duration and spatial extent.

Drought intensity describes the extent of the precipitation deficit and/or the severity of connected impacts. It is commonly measured by the derivation of a climate index from normal conditions. Commonly a drought needs some months to develop and continues for several months or years. Areas affected by severe droughts develop gradually and the regions with maximum drought intensity relocate from season to season. As the effects of drought accumulate slowly over a considerable period of time and may linger for years after the termination of the event, both onset and end of a drought are difficult to determine (Wilhite 2000).

Various drought indicators have been developed all over the world to face those challenges. Generally, four disciplinary perspectives in defining drought are considered (Wilhite and Glantz 1985). Those are: 1) meteorological drought, 2) agricultural drought, 3) hydrological drought and 4) socioeconomic drought. Realistic definitions must be specific for region and application (or impact) (Wilhite 2000). This study focuses on the characterisation of meteorological drought. Long term drought characteristics and the changes are assessed and compared, using several meteorological drought indicators implying different time scales. Those indicators are, e.g. Rainfall Anomaly Index, Percent of Normal indicator as well as decile and meteorological dry periods, using different threshold calculation concepts.

Besides variations in drought characteristics this study focuses on changes in the frequency and magnitude of heavy precipitation events on daily, monthly and seasonal time scales. Daily heavy precipitation extremes are defined using different threshold values. The absolute thresholds of 10 and 20 mm daily precipitation total are compared to percentile thresholds defined in relation to the precipitation distribution at a particular place. Monthly and seasonal wet extremes are determined using some "drought indicators", suitable to assess wet analogously to dry conditions. The same applies for wet periods.

In the first chapter some definitions, concepts and indicators used within this study are introduced. The next chapter describes the recent trends of important climate elements like temperature and precipitation as well as their extreme features, as they have been monitored on global, regional and local scales. Model results are introduced to point out possible future developments of the climate system. The statistical basis and the methodology of trend and time series analysis used for determining regional climate changes are presented in chapter 3. The climate characteristics of Saxony are introduced in the fourth chapter, as this study deals with regional climate changes in Saxony and surrounding areas. Furthermore, the data base and the quality of the used data as well some remarks on the spatial representativeness of the precipitation time series and the results of the regional classification of individual stations are discussed in this chapter.

Chapter 5 and 6 comprise the main part of this study. Chapter 5 presents the typical (heavy) precipitation and drought conditions and patterns, while chapter 6 introduces the results of the detailed trend analysis of heavy precipitation and drought events in Saxony. The characterisation of the study area and its sub-regions regarding precipitation conditions is done by calculating monthly and seasonal precipitation averages as well as displaying seasonal precipitation distributions and probability distributions of monthly precipitation totals. Drought conditions and pattern as well as heavy precipitation events and wet periods are described using different indicators based on daily and monthly precipitation data. Changes in Saxon Precipitation Characteristics are analysed for average and extreme precipitation indices. Besides, monthly and seasonal trends in precipitation totals and extremes, the spatiotemporal trend characteristics are examined using a moving 30-year trend analysis. Furthermore shifts in the annual precipitation cycle and in the probability distribution of monthly precipitation totals are analysed. Changes in duration, frequency, severity, timing and spatiotemporal characteristics are analysed for wet periods, heavy precipitation and drought events.

The last two chapters outline the main results of the study. Chapter 7 illustrated the relations between the different indicators and their connected trends and chapter 8 concludes the key findings and new research questions.

2 Theoretical Background

Climate is defined as the statistical description of weather in terms of the mean values and variability of relevant quantities like temperature, precipitation or wind over a period of time ranging from months to thousands or millions of years (IPCC 2007). Those quantities have to be averaged over a period of at least 30 years as defined by the World Meteorological Organisation. Climate in a wider sense is the state, including a statistical description, of the climate system (IPCC 2007). The climate system consists of five major components: atmosphere, hydrosphere, cryosphere, land surface (including pedosphere) and biosphere, and the interactions between them. It is a highly complex system with numerous interactions. Such interactions may result in climate feedbacks that intensify (positive feedback) or reduce (negative feedback) the initial process.

This section defines important terms like "extreme event", "drought" and "heavy precipitation" and introduces the concepts and indicators used within this study. Indicators are divided into those based on daily and those based on monthly precipitation data.

2.1 Extreme Weather and Climate Events

The relevance of extreme climate characteristics, such as droughts and wet spells, derives from their large impacts on human society and environment. Many people ask, affected by extreme weather events like the extreme flooding in the Elbe river basin in August 2002 or the extremely hot summer of 2003, whether such events are due to human impacts on climate. The answer has to be "No". Single extreme events cannot be simply and directly attributed to the anthropogenic contribution to climate change, as they are a normal feature of climate and there is always a finite possibility that a particular event may have occurred naturally. There are further problems in linking a particular extreme event to a single, specific cause, since an extreme event is usually caused by the combined effects of several parameters. The frequency of extreme events, however, might be influenced by humans. In some cases it may be possible to estimate the anthropogenic contribution to such changes via the probability of extremes' occurrence (IPCC 2007). Nevertheless, there is no doubt that the sensitivity of human society towards climate extremes is rising, as long as mankind continues to "develop" sensitive areas such as sea shores and floodplains and as long as population in such areas increase. Changes in the natural landscapes connected to human infrastructures might furthermore aggravate the impacts of extreme climate and weather events (Karl and Easterling 1999). Since extremes are an expression of the variability of climate, it is vital to analyse and understand their variability at different spatial and temporal scales (IPCC 2007).

To analyse changes in the extreme features of climate, extreme climate needs to be defined first. Extreme weather events are defined as events that are rare at a particular place and time of year. Definitions for rarity vary, but an extreme weather event would normally be as rare as or rarer than the 10^{th} or 90^{th} percentile of the observed probability density function (IPCC 2007). Hence the absolute characteristics of what is called extreme weather may differ from place to place. The term extreme climate event is used when a pattern of extreme weather persists for some time, such as a season, and especially if it yields an average or total that is extreme in itself like drought or heavy rainfall over a season (IPCC 2007).

The more extreme and thus more rare an event, the more difficult it is to identify long-term changes, simply because there are fewer cases to evaluate (Frei and Schär 2001; Klein Tank and Können 2003). Identification of changes in extremes also depends on the analysis technique employed (Trömel and Schönwiese 2005; Zhang et al. 2004). Trend analyses of extremes have traditionally

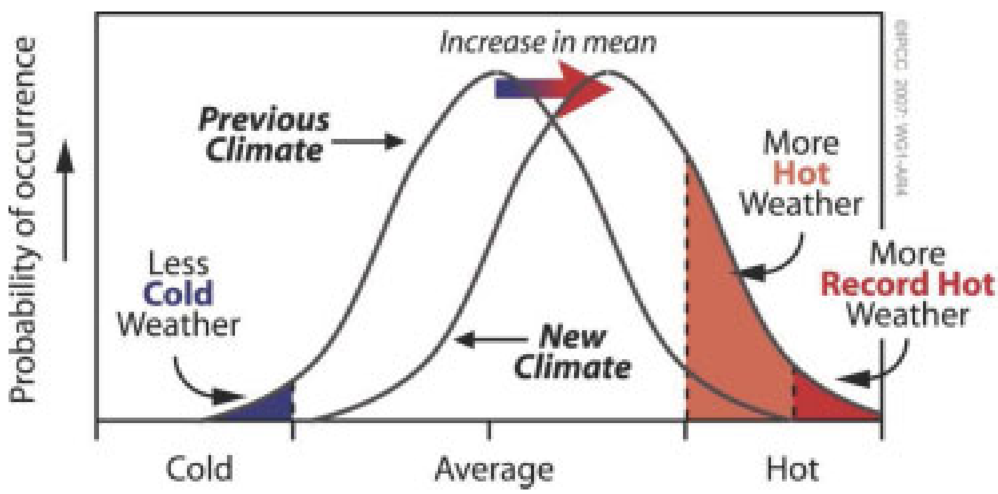


Figure 2.1: Scheme of the effect of mean temperature increases on extreme temperatures, for a normal temperature distribution (from IPCC 2007: Box TS.5).

focused on standard and robust statistics that describe moderately extreme events (between the 1st and 10th percentile) to avoid excessive statistical limitations (IPCC 2007). This study focuses on changes in these extremes.

Substantial changes in the frequency of extreme events can result from a relatively small shift in the distribution of a weather or a climate variable, as shown in Figure 2.1 for temperature extremes using a Gaussian shaped probability density function. Changes in the variability or shape of the distribution may complicate this simple picture (IPCC 2007).

The scarcity of data and regions with missing data are major obstacles for global studies of daily temperature and precipitation extremes over land (e.g., Frich et al. 2002). Homogeneous observational records with daily resolution covering multiple decades that are part of integrated digitised data sets are missing in various parts of the globe (GCOS 2003). The existing records are often inhomogeneous due to changes in observation practices or urban heat island effects (DeGaetano and Allen 2002; Vincent et al. 2002; Wijngaard et al. 2003). Those inhomogeneities exceptionally affect the understanding of extremes, as changes in extremes are often more sensitive to inhomogeneous climate monitoring practices than changes in the mean (IPCC 2007).

2.2 Drought and Dry Periods

Drought is a normal und recurring climate characteristic that might occur in almost all climate regions with varying attributes. As a temporal departure from the average it differs from the permanent climate feature of aridity that is restricted to regions with little precipitation (Hayes 2003). Generally, drought is defined relative to some long-term average of precipitation and climatic water balance, respectively. The terms “drought” and “dry period” are used synonymously within this study, although in the German language the term dry period is used to describe that there is a period dryer than the average and the term drought is often used impact related.

Concepts and Definitions: Numerous approaches in defining droughts or dry periods exist worldwide. Nevertheless, all agree that drought is a state of insufficient moisture supply caused by a precipitation deficit that accumulates over a certain period of time (e.g., Byun and Wilhite 1999; Dracup et al. 1980; Palmer 1965). Definition difficulties arise particularly from the distinct relevance of droughts in different parts of the world. In every single region drought may show different facets. Further definition problems are related to the duration of precipitation deficit accumulation and the relation of precipitation deficits to water deficits in useable water reservoirs namely soil moisture, runoff, snow cover, groundwater and artificial reservoirs. There are great differences in the timing of the precipitation event and the arrival of water in the different water reservoirs. Therefore, drought definitions depend strongly on the typical precipitation characteristics of the region and the sector they are made for.

Drought definitions may be categorized broadly as either conceptual or operational (Wilhite and Glantz 1985). Conceptual drought definitions help to describe the phenomenon and understand the concepts of drought, but they are not specific enough to exactly determine the onset and the end of a drought. Operational drought definitions aim to identify and define precise drought characteristics such as timing, duration and severity. They can be used to analyse drought frequency, severity, and duration for a given historical period (Wilhite 2000).

There is a great variety of conceptual drought definitions like:

1) *"Drought is a period of abnormal dry weather that continues long enough to cause a serious hydrological imbalance and is associated with a moisture deficit with regard to human water consumption"* (McMahon and Arenas 1982).

2) *"The main feature of drought is the decline of water availability in a certain period and in a certain area"* (Beran und Rodier 1985).

3) *"Drought is an interval of time generally in the order of months or years in duration during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply"* (Palmer 1965).

4) *"Drought is a serious shortage in the occurrence of natural water in relation to normal conditions"* (Ben-Zvi 1987).

All of those conceptual drought definitions have in common that they are vague and do not give quantitative information. Operational drought definitions try to quantify drought features. The onset of drought for example may be determined by specifying the magnitude of deviation from normal precipitation or another climate variable over a certain time unit. The threshold set for identifying the drought's onset is usually arbitrary, e.g., 75% of normal precipitation for a certain period. Thresholds are rarely based on relations to specific impacts.

The different drought definitions reflect differences in regional characteristics, user demands and disciplinary approaches. Wilhite and Glantz (1985) categorized the definitions in four basic approaches of measuring drought: meteorological, agricultural, hydrological and socioeconomic. The first three approaches try to measure drought physically and the fourth one considers drought in terms of the economic principles supply and demand. Different time scales become relevant, depending on the disciplinary perspectives (e.g. meteorological, agricultural, hydrological and socioeconomic drought).

Meteorological measurements are the first indicators of an emerging drought. They determine drought relative to some long-term mean state of balanced precipitation and evapotranspiration for a certain area – a state that is often perceived as "normal". Drought occurrence also depends on the timing of precipitation like shifts in the rain season or general seasonal influences as well as the effectiveness of precipitation like intensity and number of rainfall events. Other climate factors like high temperatures, strong winds and low relative humidity or cloud coverage may aggravate the drought severity.

The first sectors affected by a drought are agriculture and forestry due to their strong dependencies on stored soil water. An agricultural drought exists when the soil water content does not meet the needs of a distinct agricultural crop at a certain time. Agricultural droughts relate characteristics of meteorological or hydrological droughts to agricultural impacts, where the focus is on precipitation shortages, differences between actual and potential evapotranspiration, soil moisture deficits, and reduced groundwater and reservoir tables.

With continuing precipitation shortage increasingly deep soil layers become depleted. An ongoing water deficit finally affects hydrological systems and results in a depletion of surface and groundwater reservoirs. The water levels of rivers, lakes, reservoirs and groundwater as well as the extension of wetlands decline. Frequency and severity of hydrological droughts is commonly defined on the level of catchments' areas. Even though climate is the main driver of hydrological drought development, other factors like land-use changes, land degradation, and the construction of dams influence the hydrological properties of a catchment area. The impacts of hydrological droughts may even extend beyond the boundaries of the precipitation deficit area, since some regions are connected to each other by hydrological systems. Humans may alter the frequency of water shortages without changes in the frequency of meteorological droughts simply by land-use changes.

A socioeconomic drought develops, when the physical water shortage starts to affect humans. The impacts of drought on society result from an interaction of a natural event and human demands in water supply. Humans may seriously aggravate or mitigate the drought's severity. The demand for economical goods is rising in most regions, resulting from an increasing population and per-capita consumption. Due to advanced production efficiency and new technologies or the construction of reservoirs for higher water storage capacities, increases in supply are possible. The frequency of socioeconomic drought as well as the vulnerability against it increases, if demand rises faster than supply.

Droughts differ in three basic characteristics: intensity, duration and spatial extent that might be captured by various drought indicators. The drought intensity describes the extent of the precipitation deficit and/ or the severity of connected impacts. It is commonly measured by the deviation of a climate index from normal conditions. Commonly, a drought needs some months to develop and continues for months or years. Areas affected by severe droughts develop gradually and the regions with maximum drought intensity relocate from season to season.

This study focuses on general climatic changes in the region of Saxony rather than on changes in specific sectors. Therefore, analysis is done primarily for meteorological drought indicators. Those might show linkages to various sectors at different time scales with different intensities. The definition of meteorological drought has to be region-specific since the atmospheric conditions resulting in precipitation deficits are extremely variable from region to region. Some meteorological drought definitions identify dry periods based on the number of days beneath a specific threshold. This is only appropriate for regions whose precipitation regimes are comparatively uniformly distributed throughout the year. Other definitions relate actual precipitation departures to averages on monthly, seasonal or yearly time scales.

Indicators: Drought indicators assimilate a variety of data of rainfall, snow, stream flow and other hydrological indicators into one comprehensive picture (Hayes 2003). Generally, a drought indicator is a single number that is of more benefit for decision making than the raw data. While none of the indicators is superior under all circumstances, some indicators are more appropriate for certain application areas than others. One of the worldwide most frequently used indicators is the Palmer Drought Severity Index PDSI. Palmer (1965) developed a soil moisture algorithm (a model), which uses precipitation, temperature and modelled local Available Water Content of the soil. Bruwer (1990) found the PDSI to be a poor indication of short-term (i.e., periods of several weeks) changes in moisture status, affecting crops and farming operations. As the PDSI is not superior to indices than are easier to calculate (Olapido 1985; Keyantash and Dracup 2002), it is not analysed in this study. The meteorological drought indicators used in this study are described in the next paragraphs highlighting their advantages and disadvantages. First, the indicators based on monthly precipitation data are introduced, followed by those requiring daily rainfall data.

Table 2.1: Definition of drought conditions for departures from the monthly and annual mean precipitation of 1961—1990 according to the DWD (Germany's National Meteorological Service)

Precipitation total	Drier than normal	Considerably drier than normal	Extremely dry
Monthly	99 to 50%	49 to 25%	< 25%
Annual	99 to 75%	74 to 50%	< 50%

Percent of Normal (PNI): This indicator is simple by definition, easy to calculate and easily understood by a general audience. "Normal" usually refers to some long-term mean precipitation value. The PNI may be calculated for a variety of time scales (days, months, seasons or years) by dividing actual precipitation R_{actual} by normal precipitation R_{normal} which is considered to be 100 percent (Hayes 2003):

$$PNI = \frac{R_{actual}}{R_{normal}} * 100\%$$

In this study, normal precipitation was calculated for the period 1961–90 and the PNI was not only used to describe climate states drier than normal but also for wet events. The same value of PNI may have different specific impacts at different locations and therefore it is a bit of a simplistic measure of precipitation deficits. Also, the normal state may be perceived differently in different regions. Another disadvantage of using the percent of normal precipitation is the disparity of mean and median precipitation because of the missing normal distribution of precipitation on monthly or seasonal scales. Therefore, it is difficult to link a value of a deviation with a specific impact occurring as a result of the deviation.

Based on the RAI, various thresholds for defining drought are possible. Those thresholds generally depend on the time scale on which the indicator is calculated (Table 2.1).

Rainfall Anomaly Index (RAI): This index incorporates a ranking procedure to assign magnitudes to positive and negative precipitation anomalies (Van Rooy 1965), and is calculated by:

$$RAI = \pm 3 \frac{R - \overline{R}}{\overline{E} - \overline{R}},$$

where R = measured precipitation, $\overline{R}$ = average precipitation, and $\overline{E}$ = average of the ten most extreme values.

Table 2.2: Classification of RAI-values

Class of RAI-values	Description of Precipitation Characteristics
RAI > 4.00	Extremely wet
3.01 ≤ RAI ≤ 4.00	Considerably wet
2.01 ≤ RAI ≤ 3.00	Wet
1.01 ≤ RAI ≤ 2.00	Slightly wet
-1.00 ≤ RAI ≤ 1.00	Close to normal conditions
-2.00 ≤ RAI ≤ -1.01	Slightly dry
-3.00 ≤ RAI ≤ -2.01	Dry
-4.00 ≤ RAI ≤ -3.01	Considerably dry
RAI < -4.00	Extremely dry

For positive anomalies the prefix is positive and E is the average of the 10 highest precipitation values on record. Negative anomalies are calculated analogously. The index values are judged against a 9-member classification scheme (Table 2.2), ranging from extremely wet to extremely dry (van Rooy 1965). Olapido (1985) found that the differences between the RAI and the more complicated indices of Palmer (1965) and Bhalme-Mooley (1980) were negligible.

Decile Dry Periods (DD): A decile based system for monitoring meteorological drought was suggested by Gibbs and Maher (1967), who developed this indicator to avoid some of the weaknesses of the “Percent of Normal” approach. This indicator is used in the context of drought compensation programs in Australia (Coughlan 1987; Smith et al. 1993). It is calculated by generating a frequency distribution that is divided into ten parts – the deciles. The first decile is the precipitation value that is not exceeded by 10% of all precipitation totals of the time series. The deciles are categorized into five classes (Table 2.3).

Advantages of the decile indicator are the minor data and assumption requirements compared to the Palmer index. Furthermore, it provides an exact statistical measure of precipitation. Despite its easy calculation, precise calculations demand long-term data series.

The decile method may be adjusted to calculate the duration of dry periods. First the observed precipitation totals for the preceding three months are ranked against climatological records (Keyantash and Dracup 2002). Next the deciles are calculated for the total length of the precipitation record that is available for every station. As the length of the records for individual rain gauge stations differs, the period is determined for every station individually.

Table 2.3: Classification of deciles with description of precipitation characteristics

Class 1 (deciles 1 / 2)	**Class 2** (deciles 3 / 4)	**Class 3** (deciles 5 / 6)	**Class 4** (deciles 7 / 8)	**Class 5** (deciles 9 / 10)
considerably below normal	below normal	close to normal	above normal	considerably above normal

A dry period starts if the three-month-sum falls within the lowest decile (10th percentile) of the historical distribution of three month totals. Such a dry period ends, when one of two things happen: (a) the precipitation of the preceding month is in or above the fourth decile (30th percentile) of the three month totals or (b) the precipitation total for the past three months is in or above the eighth decile (70th percentile). In climates with distinct seasonal climates connected with a rainy season, the first termination rule for decile droughts might become problematic, since high monthly precipitation totals are characteristic for some times of the year and a single month with almost normal precipitation does not necessa rily have to terminate the drought. Although characterised by a seasonal climate, this should not be a problem for central Europe, as the precipitation differences between the seasons are not too high. An adjustment of the termination rules of decile droughts does not seem necessary.

Keyantash and Dracup (2002) evaluated several meteorological, hydrological and agricultural drought indicators and applied six weighted selection criteria. Overall, they found the decile indicator to be the superior meteorological drought index of the subset of drought indices they discussed.

Meteorological Dry Periods (DP): This approach is based on daily precipitation data in contrast to the drought indicators introduced so far. Numerous ways exist to define meteorological dry periods. Various thresholds exist even to assign a dry day. Some consider only days without any precipitation as a dry day and others perceive dry days as days without hydrological effective precipitation (e.g., Freydank 2001; Beck et al. 2004). The threshold for hydrological effective precipitation is generally set at 1 mm daily precipitation total. Some definition approaches for DP of different complexity are described in the following:

(1) Dietzer (2000) perceives a dry period as a *"sequence of at least eleven dry days"*.

(2) *"The UK Met Office defines the maximum number of consecutive dry days as the longest period within a year with a precipitation total of at most 2 mm at all consecutive days"* (Beck et al. 2004).

(3) Freydank (2001) describes meteorological dry periods as a *"continuous sequence of dry days, relating to days without hydrological effective precipitation (daily precipitation below 1 mm)"*.

(4) *"A dry period starts when the precipitation sum of the previous and the starting day is at most 0.5 mm and this precipitation does not exceed the potential evapotranspiration of the starting day. The dry period continues if 1) the daily precipitation is at most 0.5 mm or 2) the precipitation total of two consecutive days is less than 3 mm and below the potential evapotranspiration of those days. Such a dry time interval is considered as dry period if and only if its duration is at least 5 days and the difference of potential evapotranspiration and precipitation is a least 10 mm"* (Mühlethaler 2004).

(5) Frich et al. (2002) suggest *"the maximum number of consecutive dry days (R_d < 1 mm) as a valuable drought indicator for the dry part of the year"*.

(6) *"A dry period is a sequence of at least 4 days with maximum air temperatures above the long-term average of maximum temperature and simultaneously a relative humidity below 40% at noon (14 h)"* (OcCC 2003).

(7) *"A dry spells is defined as the number of continuous days below a threshold. The threshold refers to the 1st percentile calculated using only days with precipitation of at least 0.1 mm"* (Nicholls and Murray, 1999).

In this study the concept suggested by Dietzer (2000) is used. A meteorological dry period refers to an uninterrupted period of at least eleven days without hydrological effective precipitation (R_d < 1 mm). This concept delivers very short and intensive dry periods of limited practical relevance since every daily precipitation above 1 mm will terminate the dry period, although the drought might continue for weeks or months until the different water reservoirs are replenished. Otherwise this indicator might give evidence for changing precipitation characteristics at a shorter time scale than the other drought indicators and those changes might be signs for altered drought impacts at different sectors. Furthermore, it delivers a much larger and more significant data basis for trend analysis than the other drought indicators based on monthly data. It might be expected that its 50-year-trends are more reliable than those of monthly drought indicators.

Meteorological Dry Periods with sliding thresholds (DPST): Another concept for dealing with drought phenomena is the enhanced concept of meteorological dry periods with sliding thresholds that depend on the duration of the drought event. DPST is calculated on a daily basis like the regular meteorological dry period concept (DP) described in the previous paragraph. This concept aims at describing droughts with higher practical relevance than DP. For these purposes it uses a threshold that increases with continuing drought conditions instead of a fixed value of 1 mm daily precipitation total. For every day k a dry period continues and the precipitation deficit augments the threshold for drought termination increases by a predefined value. The threshold T_k may be raised by an absolute value V (e.g. 1 mm; $T(V)_k = k * V$) or by a relative value that takes the regional precipitation characteristics into account (e.g. 75% of normal daily precipitation $\overline{R}_d$; $T(75\%)_k = k * 0.75 * \overline{R}_d$). The two threshold definitions are compared with regard to the trend results. The precipitation falling within a dry period R_{DP} is summed up over a period k and is compared to the actual threshold T_k for every day:

$$R_{DP} = \sum_{i=1}^{k} Ri \quad \begin{cases} \text{dry period for } R_{DP} < T_k \text{ and } k \geq 30 \\ \text{no drought, otherwise} \end{cases}$$

A dry period according to this concept begins if the cumulated precipitation is for at least 30 days (one month) below the corresponding threshold. Normal daily precipitation is calculated based on the 1961—90 reference period. Further analysis is possible for the accumulated precipitation deficit within such a dry period as well as for the frequency of longer dry periods with a duration of for instance one, two or three months. DPST dry periods by definition last at least a month and quite often they last much longer than a season of year. For generating a time series, e.g. of DPST durations, it is necessary to assign the event with its duration to one month, season or year, although other periods might be affected, too. Thus, the results of trend analysis particularly for the months and seasons are strongly biased. To account for that circumstance and to get a more realistic assessment of the extent by which individual months and seasons are affected by DPST dry periods, the time series of days belonging to DPST is analysed in addition.

The acronyms and definitions of all drought and dry period indicators used within this study are summarized in Table 2.4. Each of the indices chosen can be defined for any selected season or month. The resulting time series of the chosen index has a resolution of one year, as one index value is derived per month or season, respectively.

The daily dry period indicators are calculated separately for individual stations yielding trend information with high spatial resolution. Drought indicators based on monthly data basically reflect longer term drought conditions that quite often yield insufficient data for a station based trend analysis. This is particularly true for the more severe drought events. To meet this challenge and to form a sufficient base data for trend analysis the station values are aggregated to regional time series.

Table 2.4: Acronyms and definitions of drought indicators based on daily and monthly precipitation data

	Acronym	Explanation	Unit
Dry period indicators based on daily precipitation data	N-DP	Number of meteorological dry periods (DP)	events
	N-DP-14 N-DP-21	Number of DP lasting ≥ 14/ 21 days	events
	N-DP-D	Number of days belonging to DP	days
	N-DP-D14 N-DP-D21d	Number of days belonging to DP lasting ≥ 14/ 21 days	days
	AvD-DP	Average duration of DP	days
	MxD-DP	Maximum duration of DP	days
	R-DP	Precipitation total during DP	mm
	N-DPST-1mm	Number of meteorological dry periods with a 'sliding' threshold of 1 mm (DPST-1mm)	events
	N-DPST-1mm-91 N-DPST-1mm-183	Number of DPST-1mm lasting ≥ 91/ 183 days	events
	N-DPST-1mm-D	Number of days belonging to DPST-1mm	days
	N-DPST-1mm-D91 N-DPST-1mm-D183	Number of days belonging to DPST-1mm lasting ≥ 91/ 183 days	days
	AvD-DPST-1mm	Average duration of DPST-1mm	days
	MxD-DPST-1mm	Maximum duration of DPST-1mm	days
	R-DPST-1mm	Precipitation total during DPST-1mm	mm
	N-DPST-75%	Number of meteorological dry periods with a 'sliding' threshold of 75% of normal daily precipitation (DPST-75%)	events
	N-DPST-75%-91 N-DPST-75%-183	Number of DPST-75% lasting ≥ 91/ 183 days	events
	N-DPST-75%-D	Number of days belonging to DPST-75%	days
	N-DPST-75%-D91 N-DPST-75%-D183	Number of days belonging to DPST-75% lasting ≥ 91/ 183 days	days
	AvD-DPST-75%	Average duration of DPST-75%	days
	MxD-DPST-75%	Maximum duration of DPST-75%	days
	R-DPST-75%	Precipitation total during DPST-75%	mm

Table 2.4 (continued)

	Acronym	Explanation	Unit
Monthly drought indices	N-DDP	Number of decile dry periods (DDP)	events
	AvD-DDP	Average duration of DDP	months
	MxD-DDP	Maximum duration of DDP	months
	RC-DDP	Percentage of stations affected by a DDP	%
	N-PNI75 N-PNI50 N-PNI25	Relative frequency of stations with a PNI (Percent of Normal Indicator) below 75%, 50%, 25%	%
	N-RAI-2 N-RAI-3 N-RAI-4	Relative frequency of stations with a RAI (Rainfall Anomaly Index) below -2, -3, -4	%
	Mn-PNI	Lowest PNI value	%
	Mn-RAI	Lowest RAI value	-

2.3 Heavy Precipitation and Wet Periods

Extreme precipitation events have major impacts on human society and infrastructures. Therefore, the analysis of changes in heavy precipitation events and wet periods that may result in flooding and affect agriculture or other sectors, is essential to assess the impacts of climate change. This study focuses mainly on less extreme and therefore less noisy indicators, as there are some statistical limitations in analysing the most extreme events at the very ends of the distribution, as described in section 2.1. These are expected to be more robust in indicating climatic change (Frich et al. 2002). The trends of indices for more extreme precipitation conditions, as the frequency of exceeding the 99^{th} percentile are compared to and interpreted in relation to the trends of moderate extremes.

Concepts and Definitions: Heavy precipitation events are defined as rare, extreme precipitation totals with reference to a specified duration level (DVWK 1997). There are short duration levels lasting from 5 minutes up to 24 hours and longer ones lasting from 24 to 72 hours. Since this study is based on daily to monthly precipitation values, longer duration levels are analysed.

There are different approaches to distinguish extreme events from the rest of the distribution. One common approach of defining heavy precipitation is to set up some thresholds or percentiles (Gerstengarbe and Werner 1993). The

Intergovernmental Panel on Climate Change (IPCC 2007), for instance, uses the 10^{th} or 90^{th} percentile, respectively, to define rare and thus extreme events. The threshold classification of extremes, particularly for fixed thresholds, is more or less arbitrary and its usefulness depends on the climate and the application area. A precipitation event, perceived as extreme in one area, might be associated with normal climatic conditions in another area. Thus, region-specific indicators are needed. The indicator choice has to be included in the interpretation of the trend results and the inter-region comparisons.

Thresholds for defining extreme precipitation may be absolute values like daily precipitation totals of 10 or 20 mm, or relative values defined by the precipitation distribution such as the 90^{th}, 95^{th} or 99^{th} percentile. While fixed thresholds are suitable for regions with little spatial climatological variability, they are inappropriate for regions spanning a broad range of climates (Manton et al. 2001). Next to those threshold-based indicators, various others exist, such as the simple daily intensity index or maxima of cumulated rainfall totals over a fixed number of days.

Selected indicators for heavy precipitation, monthly and seasonal precipitation extremes and wet periods are analysed and compared within this study. In the next paragraphs those indicators will be introduced shortly.

Indicators: National and regional differences in precipitation monitoring standards and procedures to ensure data quality, make it difficult to implement a standardized international reference system for precipitation indicators (Nicholls and Murray 1999). Therefore, it may sometimes be difficult to compare study results of different regions and to assess changes in global precipitation patterns, intensities and extremes. A number of international workshops (Folland et al. 1999; Nicholls and Murray 1999; Manton et al. 2001) developed sets of indicators of extreme events that should be used worldwide with the intention to ensure a global assessment of changes in extreme climate features.

These suggested **indicators based on daily precipitation data** are:

(1) Frequency of dry days ($R_d \leq 0.1$ mm d^{-1}),

(2) Frequency of wet days ($R_d \geq 1$ mm d^{-1}) or rain days ($R_d \geq 2$ mm d^{-1}, to avoid artificial trends from changes in the observation of very low rainfall),

(3) Maximum 5-day precipitation total (as an indicator for flood producing events),

(4) Number of days with precipitation ≥ 10 mm d^{-1}, ≥ 20 mm d^{-1},

(5) Frequency of exceeding specified thresholds as number of days with precipitation above the 90^{th}, 95^{th} and 99^{th} percentile (e.g., for calendar year and seasons),

(6) Variations in magnitude of thresholds,

(7) Average intensity of events greater than or equal to the threshold,

(8) Percentage of annual or seasonal precipitation falling on days with rainfall above 90^{th}, 95^{th} and 99^{th} percentiles,

(9) Simple daily precipitation intensity index (total wet day precipitation divided by the number of days with precipitation ≥ 1 mm d^{-1}),

(10) Comparison of frequency distributions of daily rainfall by using a decadal moving 30-year window (e.g., 1951—80, 1961—90, 1971—2000) with examination of variations in extremes.

The percentile thresholds are to be calculated for the 1961—1990 reference period by simple counting and/or fitting a gamma distribution. Nicholls and Murray (1999) suggest using only days with precipitation for the computation of percentiles (approach 'pd'), whereas Manton et al. (2001) use all non-missing days (approach 'ad'). Within this study both methods are used parallel and the resulting trend characteristics are compared. Table 2.5 summarizes the indicators based on daily precipitation data used within this study.

Next to analysing daily precipitation extremes, trend analysis is done for **indicators based on monthly precipitation data**. Most drought indicators derived from monthly precipitation series, such as Percent of Normal, RAI, and deciles (for definition of those indicators see section 2.3), may also be used to describe events or phases of particularly wet conditions. Decile wet periods for instance are calculated in analogue to decile droughts. The calculation is based on the historical distribution of three-month-precipitation-totals. A decile wet period starts, when the 3-month-precipitation total is within the 10^{th} decile (above 90^{th} percentile) of the historical distribution of 3-month totals (1951—2006) and lasts until precipitation returns to normal conditions with a 3-month-precipitation total within or below the 5^{th} decile (50^{th} percentile). Nicholls and Murray (1999) suggest the percentage of a country or region with precipitation in lowest or highest 5% (severe drought/wet period) or 10% (serious drought/wet period) in a year/season as an index calculated with monthly data. Wet event and period indicators used within this study are compiled in Table 2.5.

Table 2.5: Acronyms and definitions of (heavy) precipitation indices based on daily precipitation data and wet event/ period indices based on monthly precipitation data

	Acronym	Explanation	Unit
Heavy Precipitation Indices (HPI)	N-DD	Number of dry days ($P_d \leq 1$ mm)	days
	N-WD	Number of wet days ($P_d > 1$ mm)	days
	N-RD	Number of rain days ($P_d \geq 2$ mm)	days
	R-WD	Precipitation total of wet days	mm
	SDPI	Simple daily precipitation intensity index (average precipitation on wet days)	mm day^{-1}
	N-10mm N-20mm	Number of events with precipitation greater than 10 mm, 20 mm daily rainfall	days days
	N-90P N-95P N-99P	Number of events with precipitation greater than the 90th, 95th , 99th percentile of precipitation for the 1961—1990 reference period (90P, 95P/ 99P)	days days days
	Mgt-90P Mgt-95P Mgt-99P	Magnitude of the 90th, 95th, 99th percentile of precipitation	mm mm mm
	API-95P	Average precipitation intensity on days with precipitation above 95P	mm day^{-1}
	R-95P	Percentage of precipitation from events above 95P	%
	Mx-RD Mx-R3D Mx-R5D	Maximum daily, 3-day, 5-day precipitation total	mm mm mm
Monthly wet event/ period indices	N-DWP	Number of decile wet periods	events
	AvD-DWP	Average duration of decile wet periods	months
	MxD-DWP	Maximum duration of decile wet periods	months
	RC-DWP	Percentage of stations affected by a decile wet period	%
	N-PNI125 N-PNI150 N-PNI175	Relative frequency of stations with a PNI (Percent of Normal Indicator) above 125%, 150%, 175%	% % %
	N-RAI2 N-RAI3 N-RAI4	Relative frequency of stations with a RAI (Rainfall Anomaly Index) above 2, 3, 4	% % %
	Mx-PNI	Greatest PNI value	-
	Mx-RAI	Greatest RAI value	-

3 Global and Regional Climate Change

A climate variation or change exists if there is a significant change in one or more climate factors (Hupfer 1996) that persist for an extended period, typically decades or longer. Besides changes in the average conditions, variations in the standard deviation, the probability distribution as well as the extremes may characterise climate change. Climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2007).

Due to the links of the global temperature and precipitation averages to global mean radiative forcing those parameters are important to analyse, as they clearly indicate if unusual change occurs. There are complex interactions and feedbacks within the climate system. Thus, the local or regional response can be even counter-intuitive, such as regional cooling resulting from changes in planetary waves in the atmosphere (induced by global warming; IPCC 2007).

The observed global climate changes are described within this chapter on the basis of the recent 4th report of the Intergovernmental Panel on Climate Change (IPCC 2007), since the IPCC's periodic assessments of the causes, impacts and possible response strategies to climate change are the most comprehensive and up-to-date reports available on the subject. Since a consistent and transparent treatment of uncertainties is very important to assess climate change, authors of the 4th assessment report followed a brief set of guidance notes on determining and describing uncertainties in the context of an assessment. The terminology used in the report (IPCC 2007) for describing the likelihood of an outcome or result, where probabilistic estimations are possible, is given in Table 3.1.

The 4th IPCC report states that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Greenhouse gases and aerosols affect climate by altering incoming solar radiation and out-going infrared radiation that are part of Earth's energy balance. With the increased burning of fossil fuels since the start of the Industrialisation at about 1750, the global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppmv to ~385 ppmv in 2007. There are several other anthropogenic sources that significantly contribute to and affect radiative forcing. Those are for example other greenhouse gases like methane and nitrous oxide, stratospheric and tropospheric ozone as well as aerosol and surface albedo effects. Altogether, the human impact on climate during the last century greatly exceeds that due to known changes in natural processes, such as solar changes and volcanic eruptions.

The global climate changes may manifest themselves quite differently in various regions of the planet. For instance, SMUL (2005) states that regional and local tends of climate elements like temperature and precipitation do not have to match global trends under all circumstances, as the observed changes strongly depend on variations in the atmospheric circulation. Therefore, opposite tendencies may occur in different regions. The study area of central Eastern Germany (Saxony and parts of Bavaria, Thuringia, Saxony-Anhalt and Brandenburg) is part of central Europe that belongs to the warm temperate climate regime of the mid-latitudes. Therefore, it is characterised by a seasonal warm and humid climate. The characteristic westerly winds deliver wet air masses from the Atlantic and hence are often connected with precipitation. Within Germany the oceanic influence that moderates climate decreases from Northwest to Southeast (SMUL 2005). Saxony is situated in the transition zone between the more oceanic and the more continentally influenced climate regimes.

Table 3.1: Standard terms for defining the likelihood of an outcome or result (IPCC 2007: Box TS.1 Treatment of Uncertainties in the Working Group I Assessment)

Likelihood Terminology	Likelihood of the occurrence/ outcome
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

3.1 Atmospheric Circulation

Global Perspective: Teleconnections account for out of phase variations of regional climates in different locations by modulating the location and strength of storm tracks and pole ward fluxes of heat, moisture and momentum. Therefore, the understanding of their nature and changes in their behaviour is essential to conceive regional climate variability and change. Such teleconnections have direct impacts on humans, as they are often associated with droughts, floods, heat waves and cold waves. These seasonal and longer time-scale anomalies directly affect humans (IPCC 2007).

Relatively few major patterns describe atmospheric circulation variability and change to a large extent. El Niño-Southern Oscillation (ENSO) is the dominant mode of global-scale variability on inter-annual time scales, although there have been times when it was less apparent. In the Pacific sector for example, there are substantial multi-decadal variations over the 20th century with extended periods of weakened (1900–1924; 1947–1976) as well as strengthened circulation (1925–1946; 1976–2005; IPCC 2007).

El Niño is characterised by a basin-wide warming of the tropical Pacific Ocean east of the dateline. It is associated with fluctuations of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. Multi-decadal variability is also evident in the Atlantic (Atlantic Multi-decadal Oscillation) in both the atmosphere and the ocean. Many areas and most tropical monsoons were affected by the 1976–1977 climate shift, related to the phase change in the Pacific Decadal Oscillation and more frequent El Niño's (IPCC 2007).

The Southern Annular Mode (SAM) as well as the closely connected Northern Annular Mode (NAM) and the North Atlantic Oscillation (NAO) are the dominant patterns of variability in the extra tropics on monthly time scales. Teleconnection patterns tend to be most prominent in winter, when the mean circulation is strongest. For instance the NAO has the strongest signature in the winter months (December to March) when its positive (negative) phase exhibits an enhanced (diminished) Iceland Low and Azores High, respectively (Hurrell et al. 2003).

Winter surface temperatures over much of the Northern hemisphere as well as storminess and precipitation over Europe and North Africa are strongly influenced by the NAO. A positive NAO index is connected with enhanced westerly flow across the North Atlantic in winter and warm moist maritime air is moved over much of Europe. Proxy and instrumental data show evidence for intervals with prolonged positive and negative NAO index values in the last few centuries (Cook et al. 2002, Jones et al. 2003). In winter, a reversal occurred from the minimum index values in the late 1960s to strongly positive NAO index values in the mid-1990s. Since then, NAO values have declined to near the long-term mean (Figure 3.1).

Changes in atmospheric circulation like the general increase in mid-latitude westerly winds in both hemispheres are predominantly observed as 'annular modes' and relate to the zonally averaged mid-latitude westerlies. Those increased in most seasons from the 1960s to at least the mid-1990s, with pole ward displacements of corresponding Atlantic and southern polar front jet streams and enhanced storm tracks (IPCC 2007).

Independent of changes in average background conditions, all global circulation models show continued El Niño-Southern Oscillation (ENSO) inter-annual variability in the future, though with variable characteristics of change. Discernible changes in the projected ENSO amplitude or frequency in the 21st century, consistent within the recent multi-model data sets, are not verifiable at present. However, there are projected changes in the extra tropical circulation variability. The positive phases of NAM and SAM are going to increase. Regional changes in temperature, precipitation and other fields are influenced by their positive trends in annular modes. These changes would be similar to those accompanying NAM and SAM in present day climate, but interactions with global-scale changes in a future warmer climate are likely. Mid-latitude storm averages over each hemisphere are projected to decrease. This decrease is associated with the pole ward shift of the storm tracks (IPCC 2007).

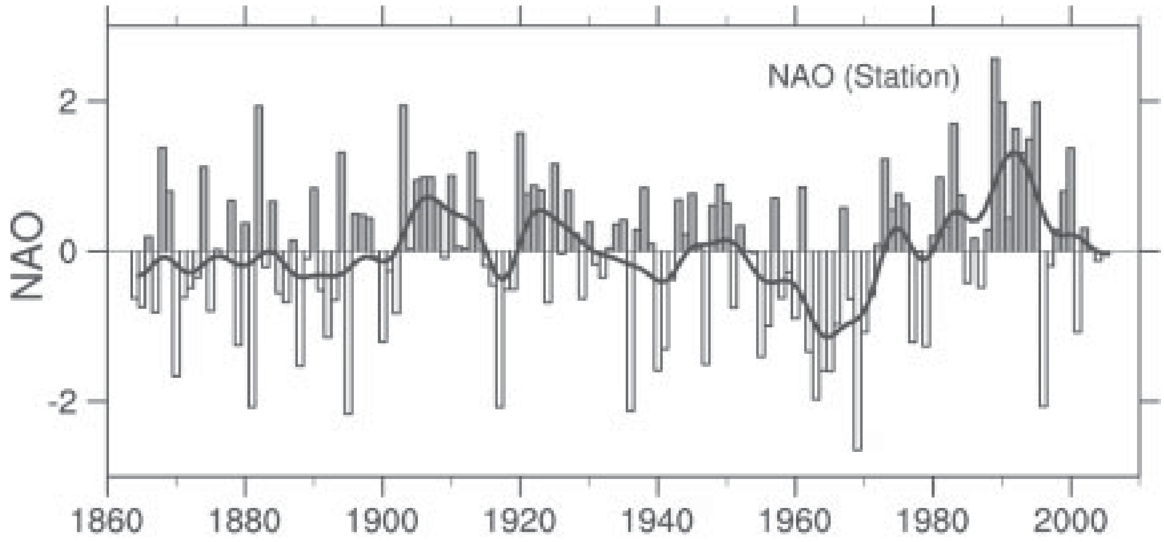


Figure 3.1: Normalised index (units of standard deviation) of the mean winter (DJFM) NAO presented as difference of normalised sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland from 1864 to 2005 (IPCC 2007: Figure 3.31)

Regional Perspective: European climate is influenced by variations in the atmospheric circulation both on inter-annual and longer time scales (IPCC 2007). As the transport and convergence of atmospheric moisture and the distribution of evaporation and precipitation over Europe is modulated by NAO/NAM (Dickson et al., 2000), changes in atmospheric circulation in the Atlantic-European space are a major reason for climate changes in central Europe (IPCC 2007). A distinctive change in large-scale circulation patterns is monitored since the 1970s with an increasing inflow of mild western air masses in winter till about the 1990s and a decrease of cool west weather conditions in summer (Figure 3.2). Hurrell et al. (2001, 2002) identified significant inter-annual to multi-decadal fluctuations in the NAO pattern in summer. The observed trend towards persistent anticyclonic flow over northern Europe has contributed to anomalously warm and dry conditions in recent decades (Rodwell 2003). The influence of Vb weather conditions, connected with persistent heavy precipitation, increases within Saxony from West to East (SMUL 2005). The pattern "Central Europe trough" (Trog Mitteleuropa) linked to the Vb-paths of cyclones shows a summerly increase during the last decades. The increase in western and south-western weather conditions since the end of the 1960s results in milder and wetter winters, whereas air masses from West and Northwest connected with cool and wet atmospheric conditions decreased in the summer months (Figure 3.2).

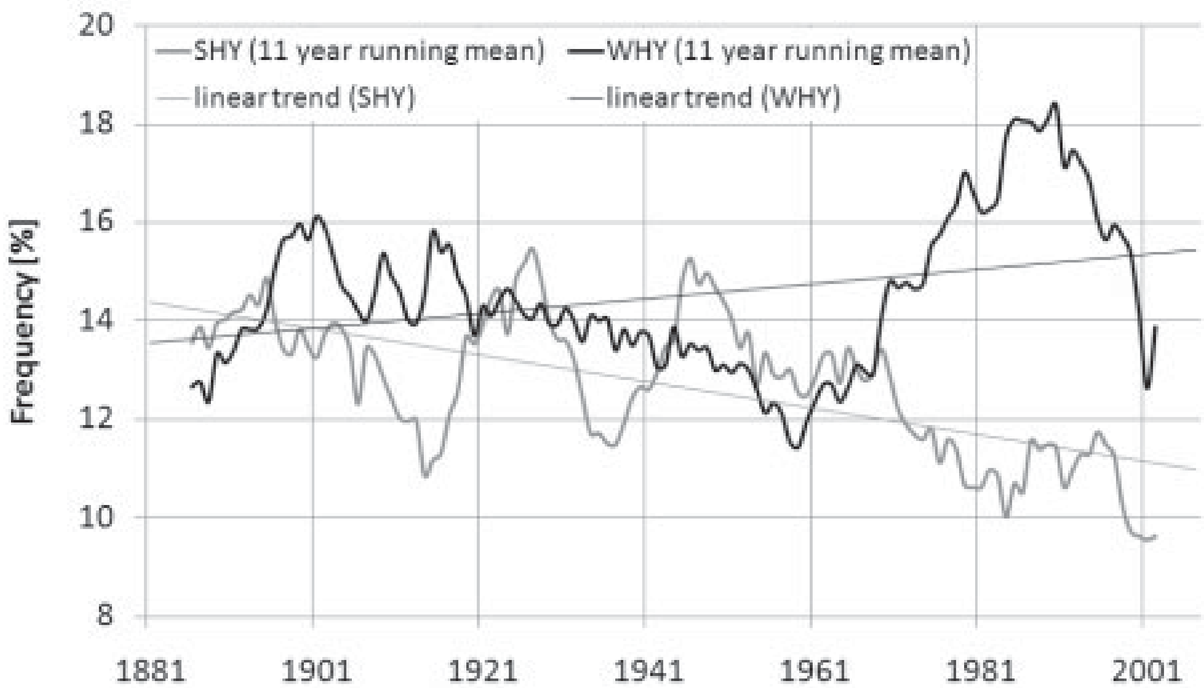


Figure 3.2: Frequency [%] of western weather conditions in central Europe for the summer and winter half year using an 11-year low pass filter, 1881—2008 (SMUL 2005, modified and completed by Hoy 2009a)

21st-century projections show a pole ward expansion of the subtropical highs, and a pole ward displacement of mid-latitude westerlies and associated storm tracks. Despite large differences in the circulation derived from global models, most regional models suggest an increased north-south pressure gradient associated by an increase in westerly flow from the Atlantic. Confidence in future changes in windiness is relatively low, but it seems more likely than not that there will be an increase in average and extreme wind speeds in northern Europe (IPCC 2007). Climate projections further show that the observed tendencies of circulation changes in central Europe continue to the 21st century (IPCC 2007) Hence, associated temperature and precipitation changes and a further spatial differentiation of climate trends have to be expected in Saxony. Distinct increases in the frequency of warm weather conditions connected with south-western air masses are likely to occur in winter (SMUL 2005).

3.2 Temperature

3.2.1 Changes in Mean Surface Temperatures

Global Perspective: Global mean surface temperatures have risen by 0.74°C ± 0.18°C (linear trend) over the last 100 years (1906–2005). This temperature increase is not linear but progressive (Figure 3.3). Eleven of the last twelve years (1995—2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The decadal trends over the last 50 year are almost twice as high as those over the last 100 years (0.13°C ± 0.03°C vs. 0.07°C ± 0.02°C per decade). The greatest warming has been observed during winter and spring in the Northern hemisphere.

All models assessed in the 4th IPCC report (2007) project for all considered non-mitigation scenarios continuing increases in global mean surface air temperature through the 21st century. Those temperature increases are driven mainly by rising greenhouse gas concentrations and the warming is expected to be proportional to the associated radiative forcing. For the early 21st century (warming averaged for 2011—2030 compared to 1980—1999) all multi-models show similar temperature increases ranging between +0.64°C and +0.69°C for CO_2 equivalent concentrations derived from the three non-mitigated IPCC Special Report on Emission Scenarios (SRES: B1, A1B and A2). The warming rate until 2030 is thus little affected by different scenario assumptions or model sensitivities and half of it would even occur if atmospheric concentrations were kept steady at year 2000 values. The scenario choice becomes more important by mid-century (2046—2065). By late century (2090—2099) the scenario differences are largest, and only about 20% of that warming arises from climate change that is already committed.

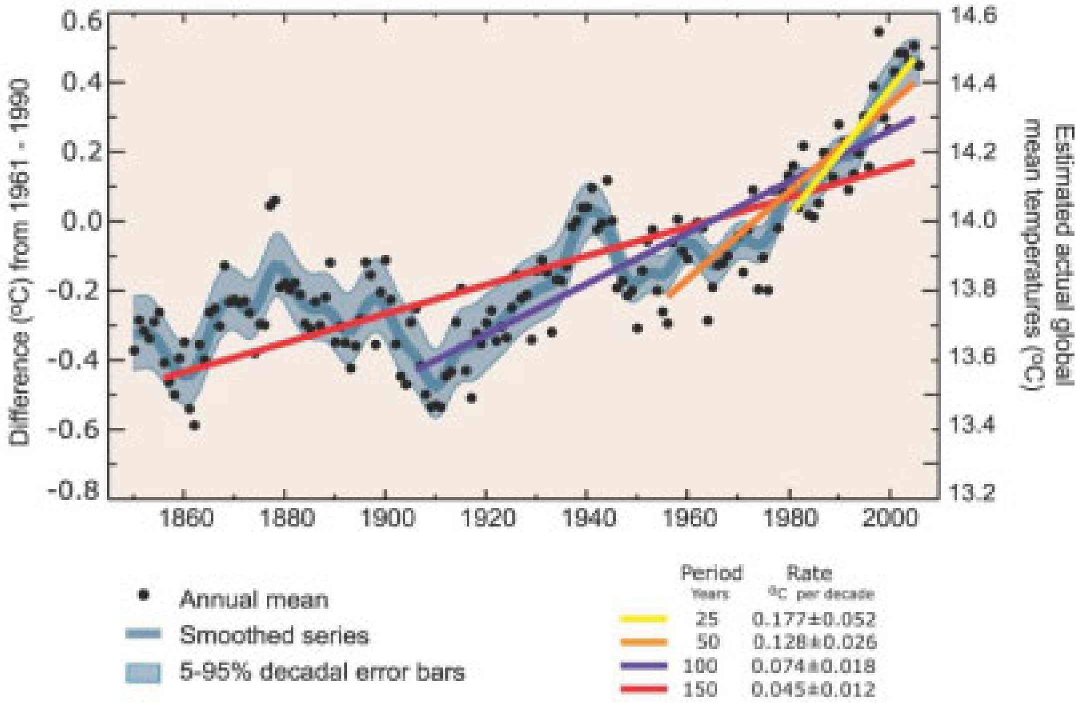


Figure 3.3: Changes in annual global mean observed temperatures changes for the last 150 years (IPCC 2007: FAQ 3.1, Figure 1)

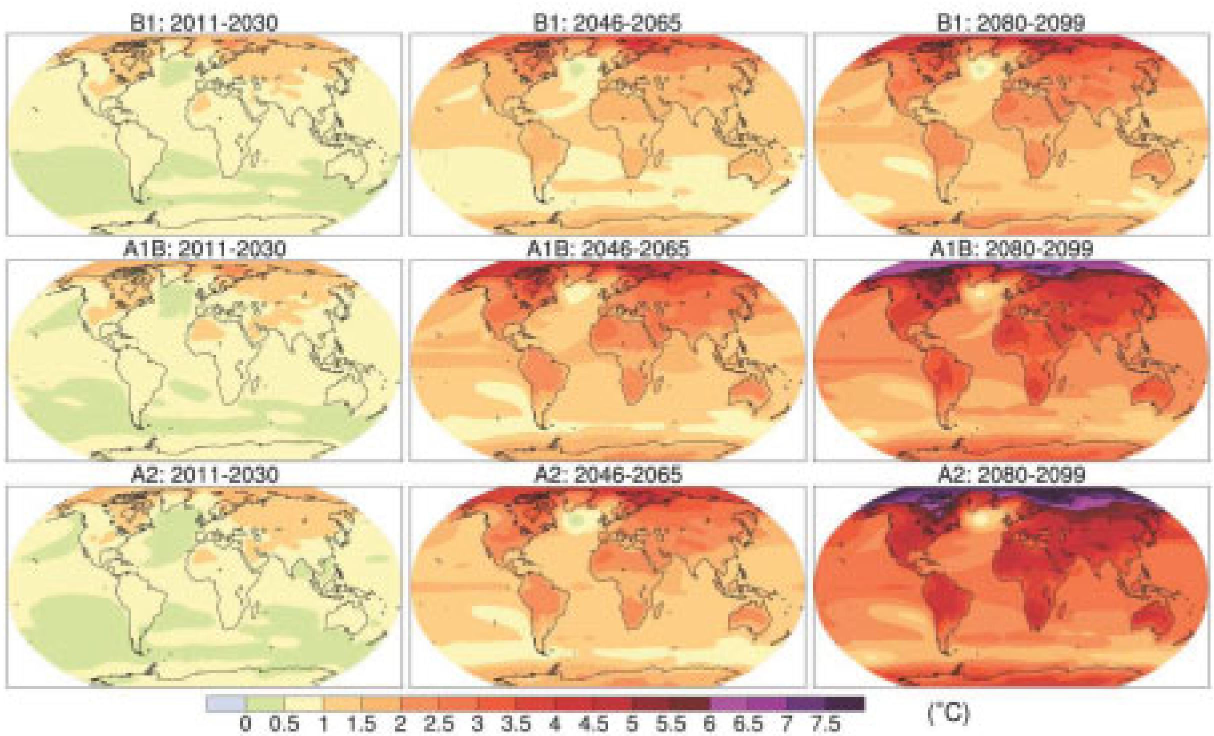


Figure 3.4: Multi-model mean of annual mean surface warming (°C) for the scenarios B1 (top), A1B (centre) and A2 (bottom), and three time periods, 2011—2030 (left), 2046—2065 (middle) and 2080—2099 (right). Anomalies are relative to the average of the period 1980—1999 (IPCC 2007: Figure 10.8)

The multi-model mean surface air temperature warming and associated uncertainty ranges for 2090 to 2099 relative to 1980 to 1999 are:

B1: +1.8°C (1.1°C to 2.9°C),
B2: +2.4°C (1.4°C to 3.8°C),
A1T: +2.4°C (1.4°C to 3.8°C),
A1B: +2.8°C (1.7°C to 4.4°C),
A2: +3.4°C (2.0°C to 5.4°C) and
A1FI: +4.0°C (2.4°C to 6.4°C).

The geographical patterns of the projected warming in the 21st century are scenario-independent (Figure 3.4) and resemble those observed over the past several decades. The greatest warming is expected to occur over land and at high northern latitudes.

Regional Perspective: European temperatures in the 20th century are characterised by a warming trend modulated by multi-decadal variability (IPCC 2007). The warming trend over Germany may be described best by a non-linear model (Schönwiese and Janoschitz 2005). Until 1850 a slight cooling was observed followed by the familiar warming by about 1°C since 1900 (Figure 3.5). The warming over Germany is greater than the global average of +0.74°C. The comparison of German temperature anomalies (Figure 3.5) with global anomalies (Figure 3.3) shows that the inter-annual variability of regional data is higher than that of global data. The warming rate over Germany for 1901 to 2000 was almost equal in all seasons, whereas spring and winter showed the highest temperature increases for 1951—2000 (Müller-Westermeier and Riecke 2006; Schönwiese et al. 2006).

A continuation of the warming trend observed in the 20th century is projected in Europe for the 21st century. The warming rate is expected to be somewhat greater than its global mean (IPCC 2007).

The warming manifests itself with spatial differentiation: in northern Europe temperature increases are likely to be largest in winter and those in the Mediterranean area largest in summer (Figure 3.6). Those projected temperature increases are not mainly due to changes in atmospheric circulation (e.g., Rauthe and Paeth 2004; Stephenson et al. 2006; van Ulden et al. 2007), although those have a significant potential to affect temperature in Europe (e.g., Dorn et al. 2003). Circulation changes enhanced the warming in most models in winter (due to an increase in westerly flow) and late summer (due to a decrease in westerly flow), but reduced the warming slightly in May and June (van Ulden and van Oldenborgh 2006).

Mean annual surface temperatures increased in the last 50 years by about 1°C all over Saxony with the greatest increase in winter (SMUL 2005). Simulations of the regional climate model WEREX project a temperature increase by about 2°C until 2050 for the moderate SRES Scenario B2. There are no distinctive spatial differences in the temperature trends, but seasonal differences with the greatest warming in winter, matching the recent developments.

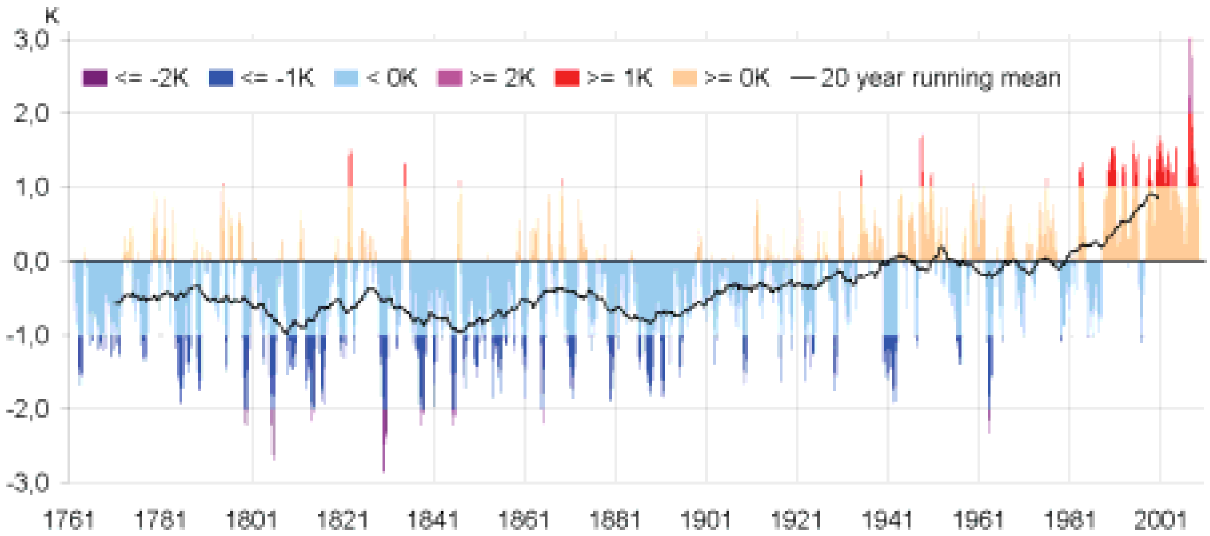


Figure 3.5: Moving 12-month anomalies of the areal mean of air surface temperature in Germany for 1761-2008 relative to 1961—1990 (Hoy 2009b)

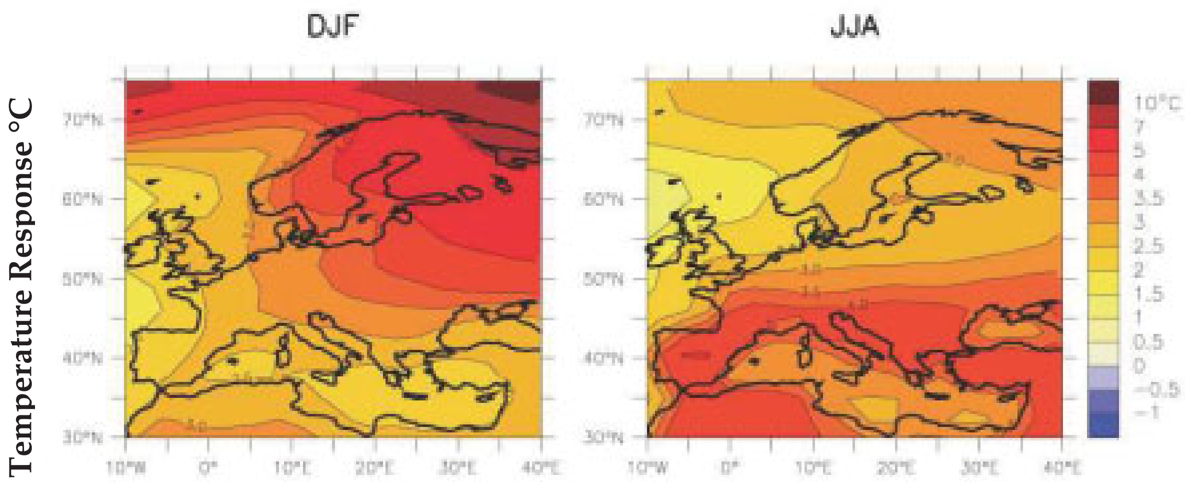


Figure 3.6: Temperature changes over Europe between 1980 to 1999 and 2080 to 2099 from the A1B simulations averaged over 21 models. Left: Winter (DJF) and Right: Summer (JJA) (IPCC 2007: Figure 11.5)

3.2.2 Temperature Variability and Extremes

Global Perspective: Besides changes in the mean climate, future changes in anthropogenic forcing will result in changes of the variability of climate. Räisänen (2002) finds a decrease in temperature variability during the cold season in the extra tropical Northern Hemisphere and a slight increase in temperature variability in low latitudes and in warm season northern mid-latitudes. Nevertheless, the significance level of these variability changes is markedly lower than that for mean climate change. The observed changes in the probability density distribution of temperature extremes like a widespread reduction in the number of frost days in mid-latitude regions, an increase in the number of warm extremes (warmest 10% of days or nights) and a reduction in the number of daily cold extremes (coldest 10% of days or nights) are consistent with the warming trend. Heat wave duration and frequency have increased during the latter half of the 20th century. The important role of moisture in moderating climate is highlighted by the very strong correlation between observed dryness and high temperatures over land in the tropics during summer.

With regard to temperature extremes, the 4th IPCC report (2007) states that more intense, more frequent and longer lasting heat waves (Figure 3.7) are very likely to occur in a future warming climate, whereas cold episodes decrease significantly. Daily minimum temperatures are projected to increase faster than daily maximum temperatures, resulting in decreasing diurnal temperature range in virtually all regions. Almost everywhere in the middle and high latitudes decreasing frost day frequencies connected with a comparable increase in growing season length are projected.

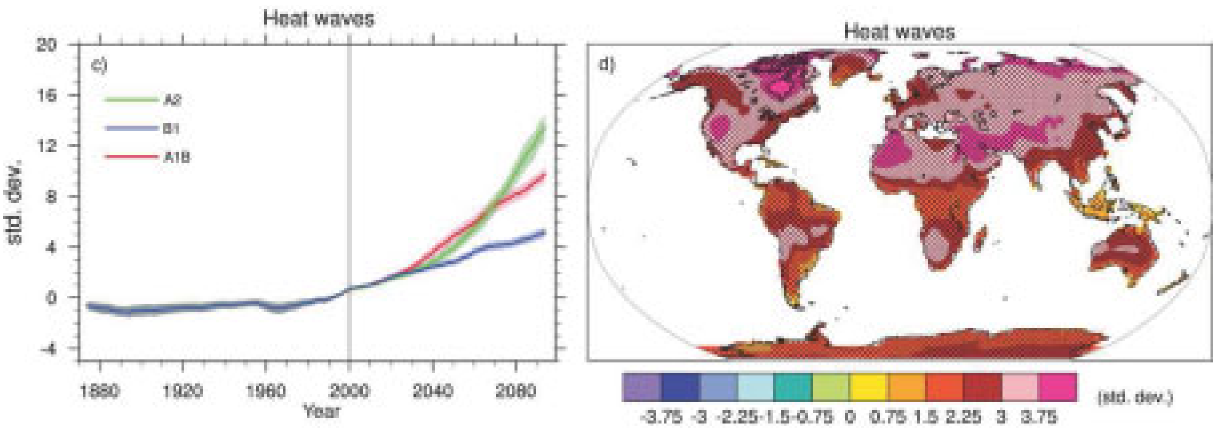


Figure 3.7: Changes in heat waves based on multi-model simulations from nine global coupled climate models for a low (SRES B1), middle (SRES A1B) and high (SRES A2) scenario. (a) Globally averaged changes. (b) Changes in spatial patterns between two 20-year means (2080—2099 minus 1980—1999) for the A1B scenario (IPCC 2007: Figure 10.19)

Regional Perspective: Changes in temperature extremes in Germany are illustrated by Figure 3.8. The probability density function of temperature has shifted to higher values while no significant changes in variance have been observed (Schönwiese et al. 2006). Thus, cold extremes declined and warm extremes increased from 1901 to 2003. Seasonally, Scherrer et al. (2005) found for Central Europe weak increases in temperature variability in summer and decreases in winter for 1961 to 2004, but these changes are not statistically significant at the 10% level. An example of an exceptional recent temperature extreme is the record-breaking heat wave over western and central Europe in the summer of 2003, whose extremes were, to a large extent, due to a continuing spring drying of the land surface over Europe. With 1.4°C above the previous warmest it was the warmest summer (JJA) since 1780.

The lowest winter temperatures in northern Europe are likely to increase more than the average winter temperatures, whereas in southern and central Europe the highest summer temperatures are likely to increase more than the average summer temperature (IPCC 2007). Heat waves are expected to increase during the summer half year in Saxony matching the global projections (SMUL 2005). Distinct decreases in cold extremes (frost and ice days) are projected as well as increases in warm extremes (summer and hot days).

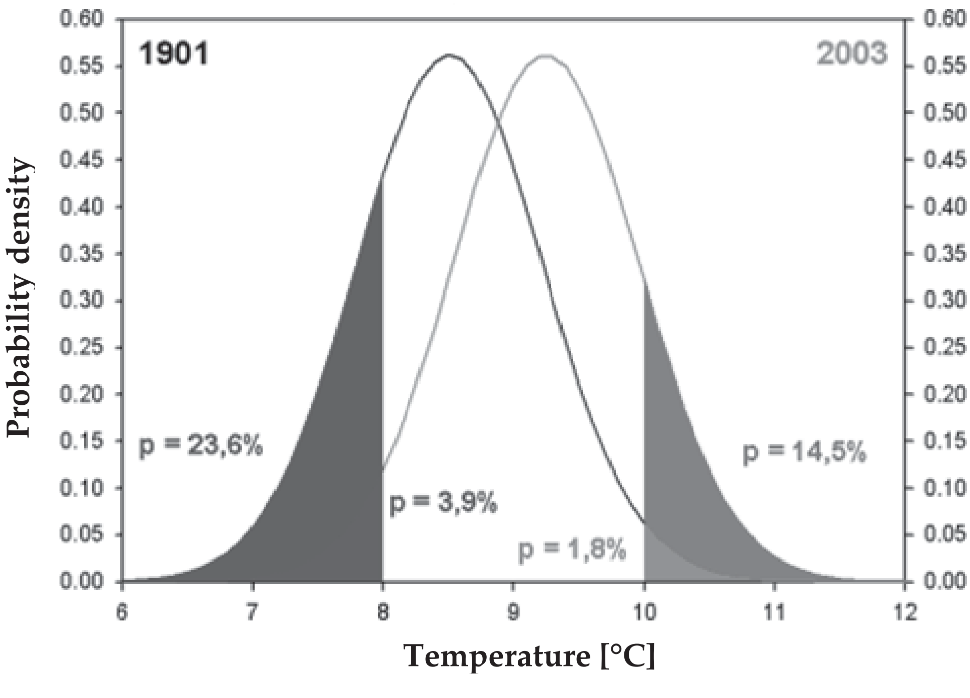


Figure 3.8: Changes in the probability density function of annual temperature for 2003 (light grey) compared to 1901 (black) with information about connected changes in exceeding or falling below certain thresholds for station Kassel (Schönwiese et al. 2006)

3.3 Tropospheric Water Vapour

Global Perspective: The increase in average atmospheric water vapour content since at least the 1980s over land and ocean is broadly consistent with the extra water vapour that warmer air can hold. For the near-surface relative humidity only very small global trends have been observed. Total column water vapour has increased over the global oceans by 1.2 ± 0.3% per decade from 1988 to 2004. Those changes are consistent in pattern and amount with changes in SST and a fairly constant relative humidity. Specific humidity shows a global average increase of 0.06 g kg^{-1} per decade (1976–2004). This corresponds to about 4.9% per 1°C warming over the globe. Trenberth et al. (2005) state that the amount of moisture in the atmosphere is expected to increase in a warming climate because saturation vapour pressure increases with temperature according to the Clausius-Clapeyron equation. Therefore, further increases of globally averaged mean water vapour are projected for the 21st century.

Regional Perspective: Analyses for central Europe show that changes in integrated water vapour are strongly coupled to the surface temperature, with regions of warming experiencing increasing moisture and regions of cooling experiencing decreasing moisture (Philipona et al. 2005). Auer et al. (2007) demonstrated increasing moisture trends for central Europe.

Apart from circulation changes, precipitation change pattern are strongly influenced by the increased moisture transport capacity of a warmer atmosphere. Due to larger continental warming compared to surrounding marine areas relative humidity in summer is going to decrease in continental and south-eastern Europe (IPCC 2007).

3.4 Precipitation

3.4.1 Mean Precipitation Trends

Global Perspective: Changes in precipitation are observed as changes in type, amount, frequency, intensity and duration. The increases in atmospheric water vapour implicate increases in precipitation intensity. This will lead to reduced frequency or duration, if the total evaporation rate from the Earth's surface (land and ocean) is unchanged. In the trends of hydrological variables substantial uncertainty remains due to large regional differences, gaps in spatial coverage and temporal limitations in the data (Huntington 2006). Patterns of precipitation change are more spatially and seasonally variable than temperature change. Generally, precipitation over land increased over the 20th century from 30°N to 85°N (Figure 3.9). Distinct precipitation increases were also observed from 10°N to 30°N for period 1900—1950, but after about 1970 precipitation declined in those latitudes. Downward trends are present in the inner tropics from 10°N to 10°S, especially after 1976/1977.

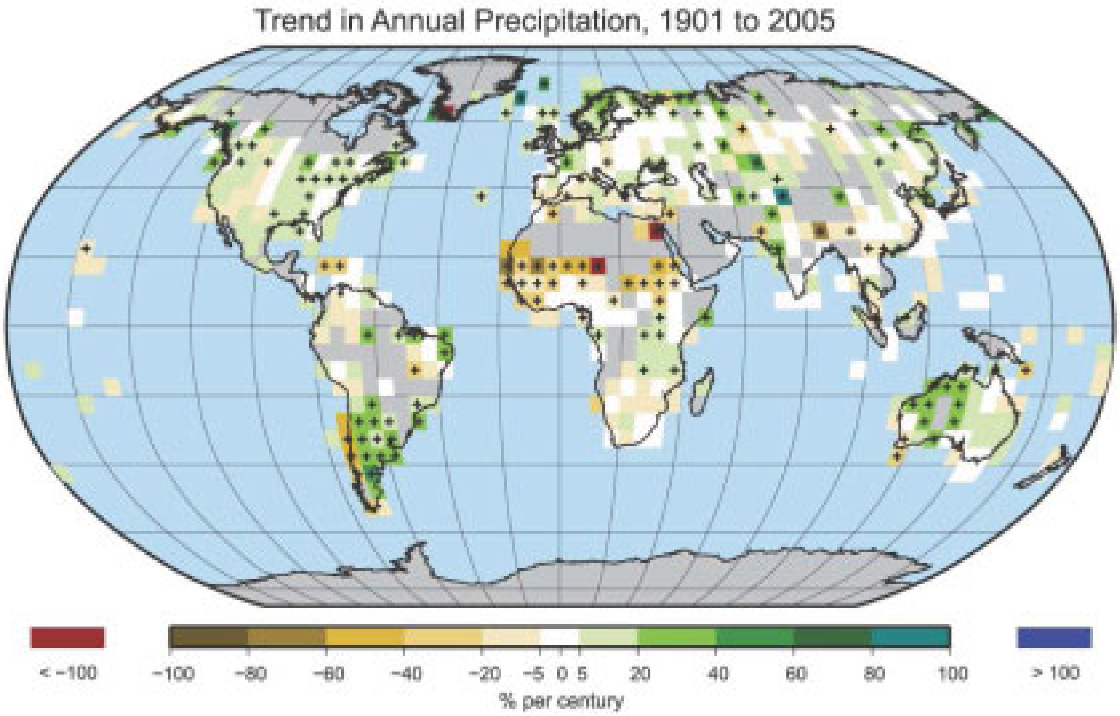


Figure 3.9: Trend of annual land precipitation amounts for 1901 to 2005 (% per century based on 1961—1990 means). Areas in grey have insufficient data to produce reliable trends. Trends significant at the 5% level are indicated by black + marks (IPCC 2007: Figure 3.13)

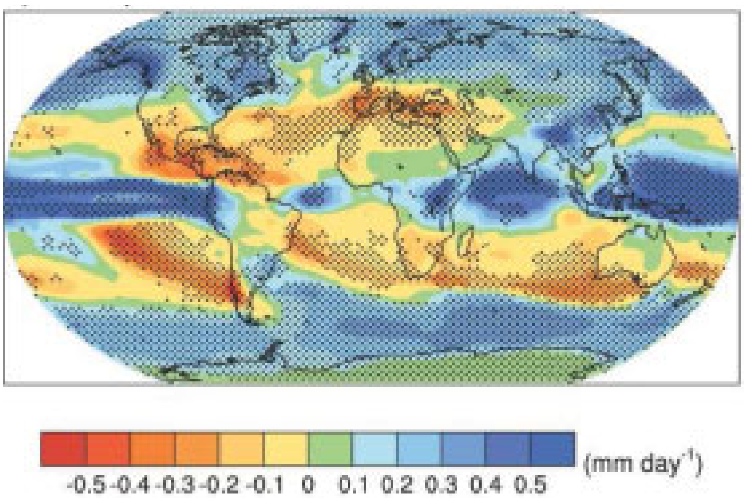


Figure 3.10: Multi-model mean changes in annual mean precipitation (mm day^{-1}) for the SRES A1B scenario for period 2080 to 2099 relative to 1980 to 1999 (IPCC 2007: Figure 10.12)

Regions with significant precipitation changes show matching changes in stream flow as higher latitudes showing increasing runoff and river discharge. River discharges in many tropical areas of Africa and South America are strongly affected by ENSO.

Although, models simulate for all scenarios an increasing global mean precipitation with global warming, there are substantial spatial and seasonal variations not only in the multi-model mean but also in the magnitude of change among the model ensembles. Precipitation increases are very consistent across models in both seasons at high latitudes. Decreases in precipitation are evident in the multi-model ensemble mean over many subtropical areas (Figure 3.10). Mid-latitude summer precipitation decreased in many regions, except for increases in eastern Asia. Precipitation generally increases in the areas of regional tropical precipitation maxima such as the monsoon regimes.

The increase in global mean precipitation indicates an intensification of the hydrological cycle, associated with increased water-holding capacity of the atmosphere in addition to other processes (Douville et al. 2002). The multi model mean varies approximately in proportion to the mean warming. Expressed as a percentage of the mean simulated change for 1980 to 1999 (2.83 mm day^{-1}), the rate varies from about 1.4% per °C in A2 to 2.3% per °C in the constant composition commitment experiment. The increases in extreme precipitation events are even higher, consistent with energetic constraints. In most areas also increases in the monthly mean precipitation variability are found, but with lower significance levels than for mean climate changes (Räisänen 2002).

Regional Perspective: Precipitation over Germany increased in the 20^{th} century from about 735 mm to approximately 800 mm with considerable interannual variations (Schönwiese and Janoschitz 2005). The likely opposite seasonal trends in central Europe with increasing winter precipitation but a decrease in summer stated by the IPCC (2007) have also been observed in Germany. Schönwiese and Janoschitz (2005) described inverse seasonal precipitation trends, a slight decrease in summer and distinct increases in winter. The intensified increase in winter temperatures during the last decades is connected with a likewise intensified increase in winter precipitation (Schönwiese and Janoschitz 2005). Rapp (2000) attributes those increases in winter precipitation to an intensified zonal circulation in the midlatitudes. The spatial patterns of precipitation changes are much more variable than those of temperature changes (Rapp 2000). The lee-effect of German low mountain ranges has distinct impacts on the regional precipitation patterns particularly for the frequent western circulation pattern and besides the reductions in total precipitation it also reduces the precipitation trend. This orographic effect is particularly obvious in Eastern Germany (Rapp 2000).

Analysis for the region Saxony show that the hydrological effective precipitation (daily precipitation totals ≥ 1 mm) has increased (Freydank 2001), whereas annual precipitation totals generally show no or just small trends (Hänsel et al. 2005). This is due to a decreasing frequency of dry days (daily precipitation totals < 1 mm) and reverse trend developments in the seasons. The summer half year (April to September) became drier with particularly high decreases in precipitation totals in the agriculturally used lowlands in the North of Saxony, whereas the winter half year (October to March) became more wet (Franke et al. 2004; Hänsel et al. 2005). The winterly precipitation increases north of the mountain ridge of the Erzgebirge are lower than in other Saxon areas due to foehn wind effects (SMUL 2005). Days with snow cover decreased significantly not only in the lower areas but also in the mountains. The decreasing tend for the highest mountain in Saxony Fichtelberg is rather extreme for 1951—2000. A continuation of this trend would reduce the days with snow cover above 20 cm at about 100 days on average in 100 years (Freydank 2001).

Model projections predict further increases in annual mean precipitation in northern Europe, whereas in most of the Mediterranean area very likely annual mean decreases occur matching the observations of the 20th century (Figure 3.11). Variations in the spatial precipitation changes over Europe are sensitive to changes in atmospheric circulation namely changes in NAO. Southern Europe and parts of central Europe are characterised by a drier winter (DJF) during the positive phase of the NAO, while the reverse is true in the British Isles, Fennoscandia and north-western Russia (IPCC 2007). Therefore, differences in the simulated circulation changes among the individual models were accompanied by large differences in precipitation change, particularly in summer. Nevertheless, most models project increases in winter precipitation for central Europe, enhanced by increased westerly winds and decreases in summer precipitation, largely due to more easterly and anticyclonic flow (Figure 3.11). Those changes are classified as likely. Snow season length is very likely to decrease and deceases in snow depth are likely in most of Europe (IPCC 2007).

Besides circulation changes thermodynamic factors appear to affect the simulated seasonal cycle of precipitation changes in Europe, particularly in summer (Rowell and Jones 2006). These included reduced relative humidity resulting from larger continental warming compared to surrounding sea areas and reduced soil moisture due mainly to spring warming causing earlier snowmelt.

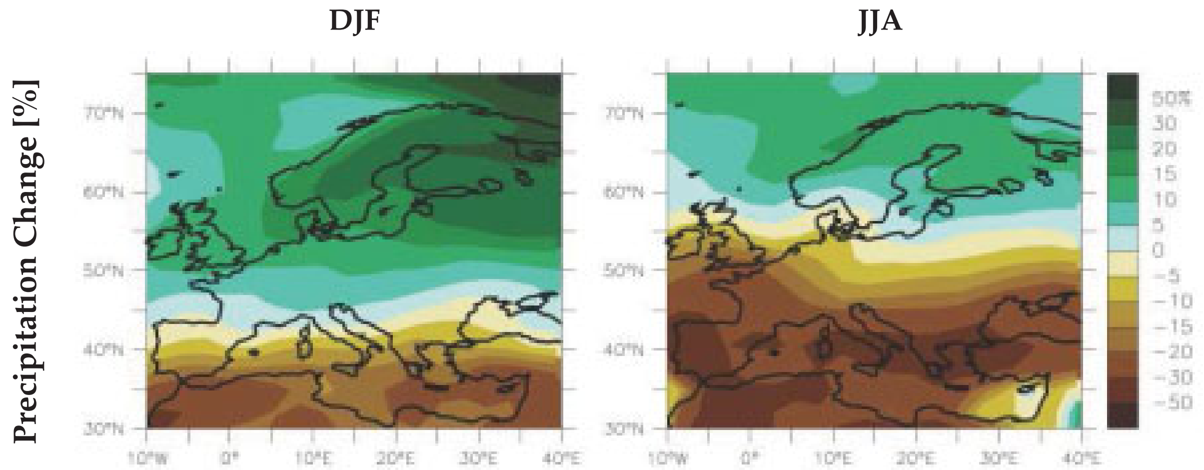


Figure 3.11: Precipitation changes [%] over Europe between 1980 to 1999 and 2080 to 2099 from the A1B simulations averaged over 21 models. Left: Annual mean, Centre: Winter (DJF) and Right: Summer (JJA) (IPCC 2007: Figure 11.5)

For Saxony, precipitation increases are projected in winter, whereas distinctive precipitation decreases are expected for the summer months. There are large spatial variations in the simulated precipitation changes like already described for global scales. In summer (JJA) large precipitation decreases, by about 15% to 30% in Northern and Eastern Saxony, face slight precipitation increases in the Western Erzgebirge and Vogtland (SMUL 2005). The projected increasing frequency of mild south-westerly air masses in winter will enhance lee-effects and connected precipitation reduction north of the Erzgebirge matching the already observed tendencies (SMUL 2005).

3.4.2 Changes in Precipitation Extremes and Droughts

Global Perspective: Consistent with a warming climate and observed significantly increasing amounts of water vapour in the atmosphere, an increase in the number of heavy precipitation events (e.g., 95th percentile) is likely within many land regions. Such frequency increases are also likely in regions with reductions in total precipitation amount.

Data from Europe and the USA document that the relative increase in precipitation extremes is larger than the increase in mean precipitation. This becomes manifest in an increasing contribution of heavy precipitation events to total precipitation (Groisman et al. 2004; Klein Tank and Können 2003). The gridded extreme indices for precipitation (Alexander et al. 2006) show that changes in precipitation extremes are much less coherent than for temperature (Figure 3.12). The percentage contribution to total annual precipitation from very wet days (upper 5%; global average over land area with sufficient data), however, is greater in recent decades than in earlier ones. The thresholds for intense precipitation vary geographically between the 90th and 99.9th percentile of daily precipitation events. Changes in intense precipitation for more than one half of the global land area indicate an increasing probability of intense precipitation events beyond that expected from changes in the mean for many extra tropical regions (Groisman et al. 2005). For the extreme tail of the distribution (several-decade return periods) there is evidence that the changes are consistent with changes inferred for more robust statistics based on percentiles between the 75th and 95th levels. For a reliable trend assessment, however, practically no region offer sufficient data.

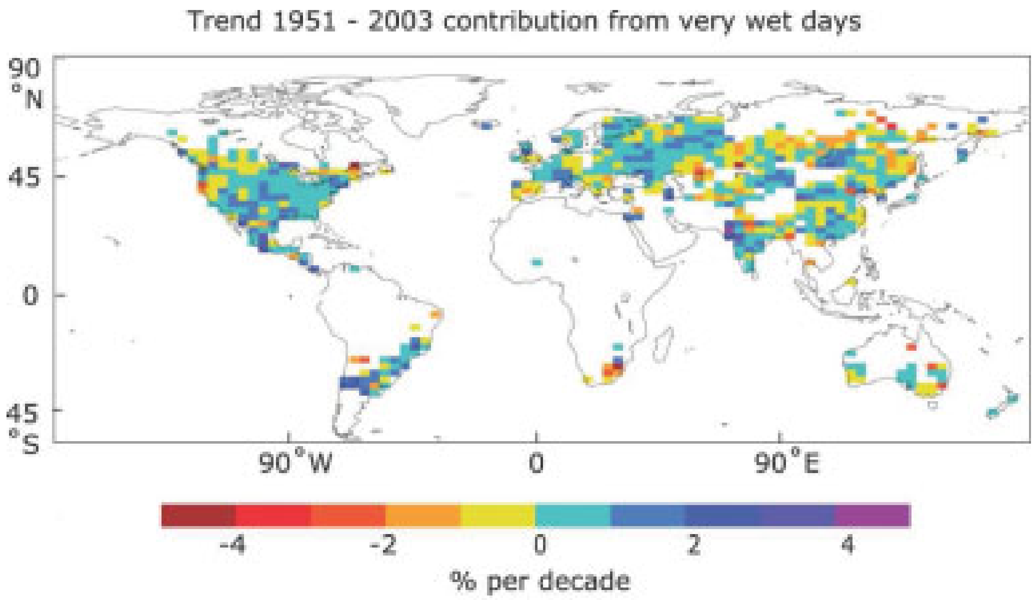


Figure 3.12: Observed trends (% per decade) for 1951—2003 in the contribution to total annual precipitation from very wet days (95th percentile) (IPCC 2007: Fig. 3.39)

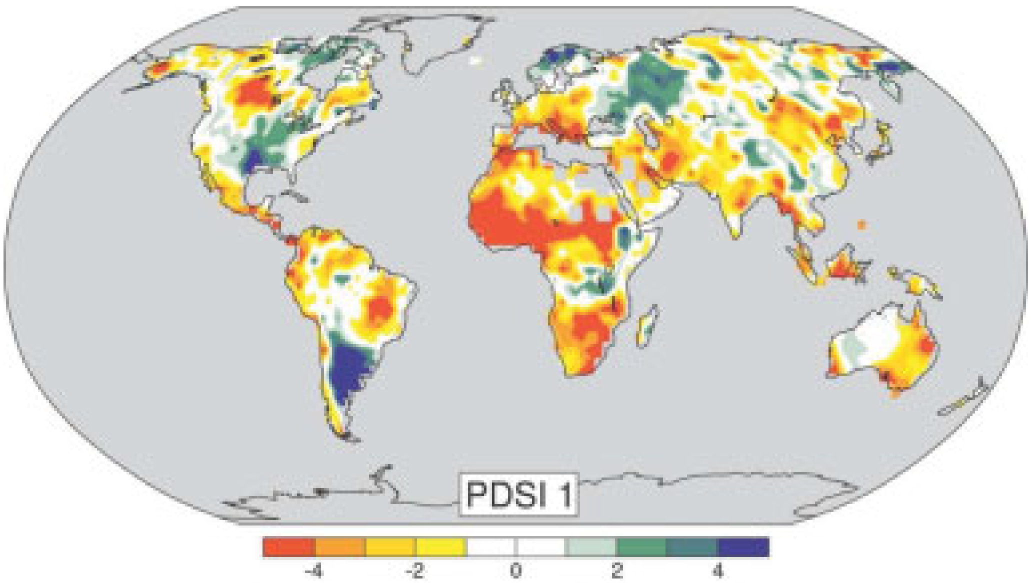


Figure 3.13: The most important spatial pattern of the monthly Palmer Drought Severity Index (PDSI) for 1900 to 2002. (IPCC 2007: FAQ 3.2, Fig. 1)

More intense and longer droughts have been observed over wider areas, particularly in the tropics and subtropics, since the 1970s. Enhanced evapotranspiration and drying due to decreased land precipitation and increased temperatures are important factors that have contributed to more regions experiencing droughts, as measured by the Palmer Drought Severity Index. Dai et al. (2004) found a large drying trend over NH land since the mid 1950s, with widespread drying over much of Eurasia, northern Africa, Canada and Alaska (Figure 3.13).

Globally, very dry areas, which are defined as land areas with a PDSI of less than -3.0 increased from about 12% to 30% since the 1970s due to surface warming. A large jump in very dry areas occurred in the early 1980s due to an ENSO-related precipitation decrease over land (Dai et al. 2004). Factors that determine the regions where droughts have occurred are changes in SSTs (especially in the tropics) and associated changes in the atmospheric circulation and precipitation as well as diminishing snow pack and subsequent reductions in soil moisture (in the western USA). Recent droughts in Australia and Europe have been accompanied by extremely high temperatures and heat waves, as had already been assumed from general considerations on global climate change.

Modelled increases in precipitation extremes are even higher than those in mean in most tropical and mid- and high-latitude areas (Kharin and Zwiers 2005). The models project an increase of dry days (Figure 3.14 c and d) and connected drought risk, and at the same time an increase in the intensity of precipitation events (Figure 3.14 a and b) and associated flooding. Barnett et al. (2006) noted that increases in the frequency of dry days do not necessarily mean a decrease in the frequency of extreme high rainfall events depending on the threshold used to define such events.

The highest increases in precipitation intensity are projected for tropical and high latitude areas that also experience increases in mean precipitation. Precipitation intensity increases are forecasted even in areas where mean precipitation decreases (most subtropical and mid-latitude regions) accompanied by longer periods of little rainfall in between. Intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration, particularly in the subtropics (Allen and Ingram 2002; Beniston 2004; Christensen and Christensen 2003, 2004; Frei et al. 1998; Meehl et al. 2005; Pal et al. 2004; Palmer and Räisänen 2002).

Wet extremes are projected to become more severe in many areas where mean precipitation increases, and dry extremes where mean precipitation decreases (Kharin and Zwiers 2005; Meehl et al. 2005; Räisänen 2005; Barnett et al. 2006).

However, changes in the frequency of extreme precipitation at an individual location can be difficult to estimate due to model parameterisation uncertainty (Barnett et al. 2006). Time scale might be another important factor, whereby frequency increases of seasonal mean rainfall extremes can be greater than the increases in the frequency of daily extremes (Barnett et al. 2006).

The tendency for drying of the mid-continental areas during summer as projected by the models for a future warmer climate (although there is a large range in the amplitude of summer dryness across models) indicates a greater risk of droughts in those regions. Droughts associated with this summer drying could result in regional vegetation die-offs (Breshears et al. 2005) and contribute to an increase in the percentage of land area experiencing drought at any one time. Extreme drought is expected to increase from 1% of present-day land area to 30% by the end of the century in the A2 scenario (Burke et al. 2006). Drier soil conditions can also contribute to more severe heat waves (Brabson et al. 2005).

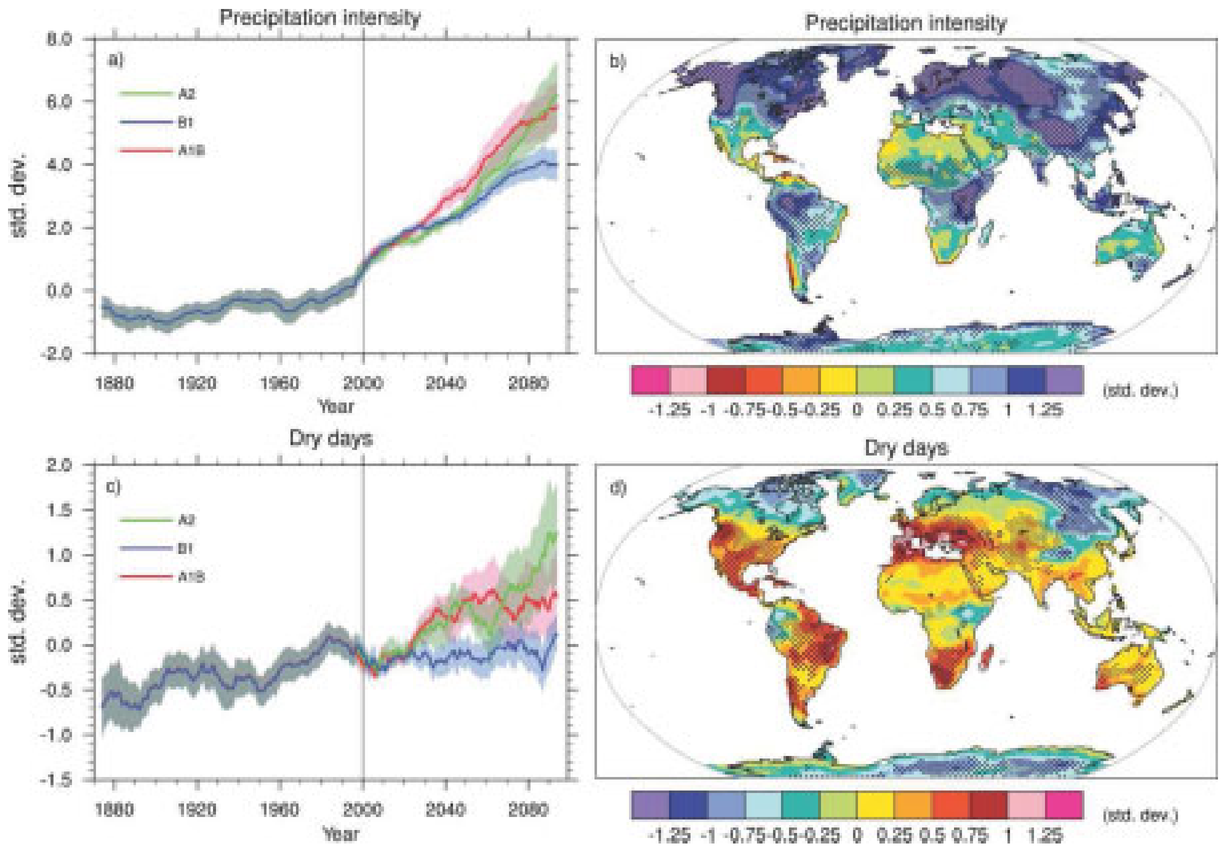


Figure 3.14: Changes in extremes based on multi-model simulations from nine global coupled climate models for a low (SRES B1), middle (SRES A1B) and high (SRES A2) scenario, (a) Globally averaged changes in precipitation intensity. (b) Changes in spatial patterns of simulated precipitation intensity. (c) Globally averaged changes in dry days. (d) Changes in spatial patterns of simulated dry days. Changes in (b) and (d) are between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. (IPCC 2007: Fig. 10.18)

Regional Perspective: The 4th IPCC report (IPCC 2007) states a likely increase in extremes of daily precipitation for northern Europe, whilst deceases in the annual number of precipitation days are very likely in the Mediterranean area. In Europe the number of moderately and very wet days (defined as wet days (≥1 mm of rain) that exceed the 75th and 95th percentiles, respectively) has increased over large areas during the second half of the 20th century (Klein Tank and Können 2003; Haylock and Goodess 2004; OcCC 2003). Malitz et al. (2005) found changes in heavy precipitation at different time scales and return periods in Germany. Intensive precipitation with a yearly return period has increased since the 1950s. Even higher increases in precipitation amounts since 1941 were observed at station Kempten for return periods of 100 years. Heavy precipitation with duration levels of 24 hours increased particularly in the north-western parts of Germany and in Northern Baden Wuerttemberg.

Seasonally, Malitz et al. (2005) described more differentiated developments. Some German regions show winterly increases in precipitation intensity, whereas the summer trends were regionally more diverse. Nevertheless, serious heavy precipitation events might occur in years with dry summers or in regions with trends to increasing summer dryness. Statistical significant trends towards increasing frequency of heavy precipitation events are monitored at more stations than trends of increasing precipitation intensity, particularly in winter (Malitz et al. 2005). Many trends observed by Malitz et al. (2005) are progressive, particularly in winter and intensified during the 20th century.

Unlike temperature, there is evidence for increasing variance of precipitation over Germany (Jonas et al. 2005; Trömel 2005). Figure 3.15 shows changes in the probability density function of precipitation for summer and winter. Winter precipitation is not only characterised by a shift in mode to higher values, but rather a considerable increase in variance. This yields an increase in the occurrence probabilities of very high and very low precipitation values at the same time. Reverse developments have been observed for summer. Due to decreases in variance the occurrence probability of very low precipitation events declined despite lower mean precipitation values (Schönwiese et al. 2006).

The trends of heavy precipitation events depend upon the thresholds chosen to define such an event. For small thresholds like 10 mm daily precipitation, minor decreases in the frequency of heavy precipitation events have been observed throughout the year in all parts of Saxony for the period 1951 to 2000 (Freydank 2001). Those decreases (thresholds of 10 mm, 90th and 95th percentile) are most pronounced during the summer half year, whereas the winter half year shows an increase in frequency and intensity of heavy precipitation events matching the general precipitation trends (Hänsel et al. 2005).

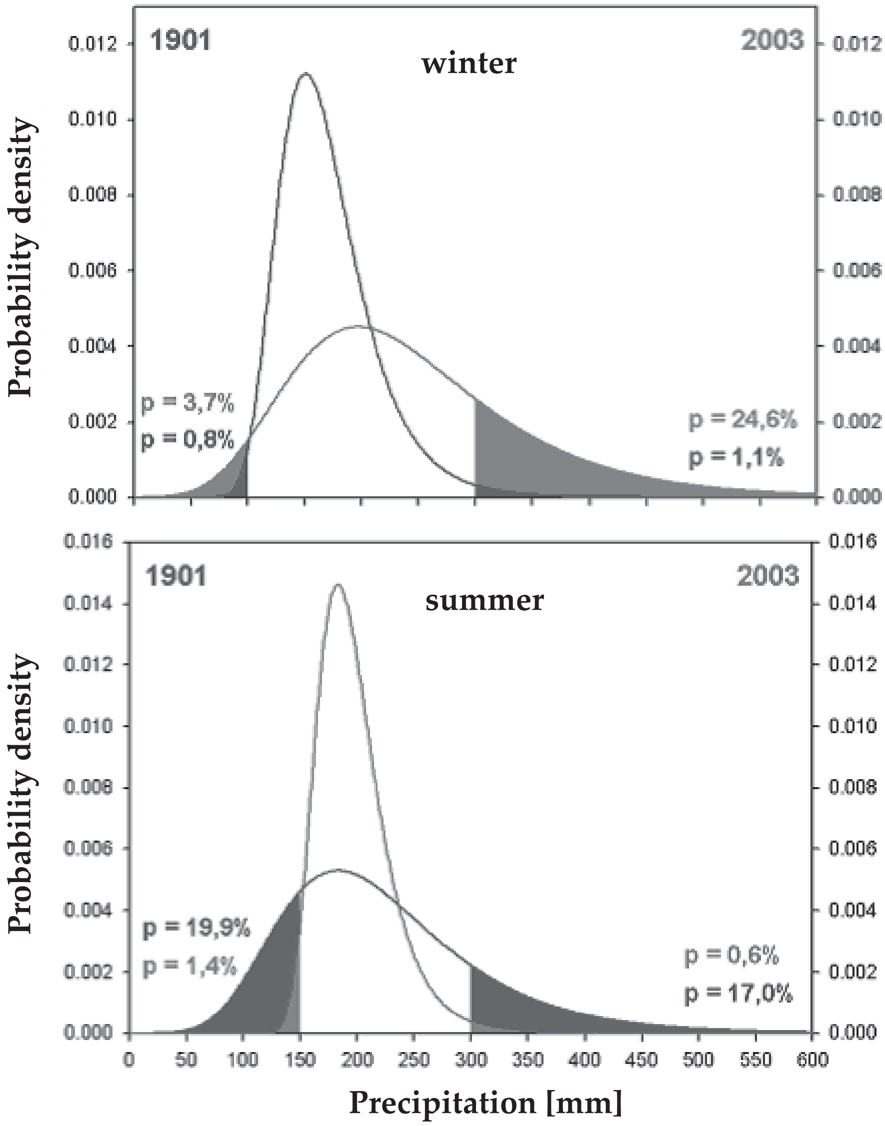


Figure 3.15: Changes in the probability density function of seasonal precipitation totals (left: winter, right: summer) for 2003 (light grey) compared to 1901 (dark grey) with information about connected changes in exceeding or falling below certain thresholds for station Eppenrod (near Limburg) (Schönwiese et al. 2006)

For higher thresholds like 20 mm daily precipitation or the 99th percentile more stations show positive summer half year trends although the maximum daily precipitation height during the summer half year has deceased. The winter half year shows increases in the frequency as well as intensity of extreme precipitation events (99th percentile; Hänsel et al. 2005). Freydank (2001) described significant increases in heavy precipitation events (thresholds of 10 or 20 mm daily precipitation) in July and August.

Dryness measured in dry day frequency or frequency and duration of meteorological dry periods increased during the summer and decreased during the winter half year (1951—2000, Hänsel et al. 2005). In vegetation period I (April, May, June) the number of precipitation days has decreased for period 1951 to

2000 with an accelerated drying in most Saxon areas in 1971—2000 (Freydank 2001). Those negative trends are highest in the Northern parts of Saxony bordering Brandenburg and at the western slopes of the Erzgebirge. The trend towards increasing dryness in vegetation period I is also supported by increases in dry day frequency and maximum duration of the meteorological dry period (Freydank 2001).

Connected with very likely annual mean precipitation increases, extremes of daily precipitation are also likely to increase in most of Northern Europe (IPCC 2007). The increased likelihood of very wet winters over much of central and northern Europe, which is due to an increase in intense precipitation associated with mid-latitude storms, suggests more floods across Europe (Palmer and Räisänen 2002). Christensen and Christensen (2003) conclude that there could also be an increased risk of summer flooding in Europe. The mean decrease in summer precipitation predicted for the 21st century is going along with an increase in drought risk, particularly in Central Europe and the Mediterranean area (IPCC 2007). With respect to drought events, an increasing risk of summer drought is likely in central Europe and in the Mediterranean area.

Although a further drying trend is predicted for the summer half year, days with extreme precipitation and thus the intensity of local showers and thunderstorms are going to increase, too (Figure 3.16; SMUL 2005). In winter, however, no significant changes in extreme precipitation events are projected despite increases in average precipitation amounts.

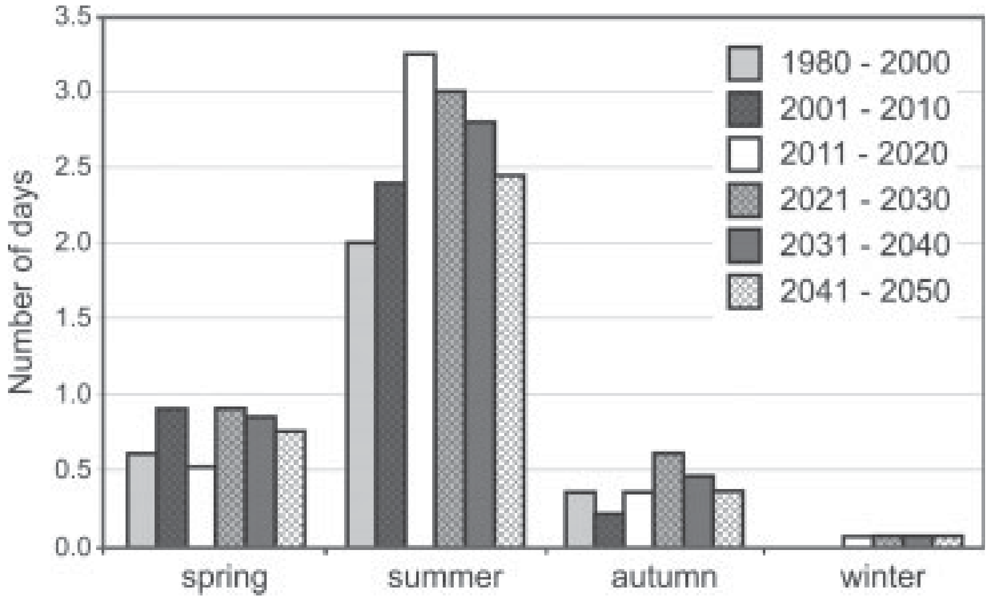


Figure 3.16: Number of days with precipitation above 55 mm within the four seasons for the observational period 1980-2000 and 5 projected periods (2001—2010 to 2041—2050; SMUL 2005)

4 Trend and Time Series Analysis

The term trend refers to long-term changes in one or more of the climate elements or derived parameters; thus a trend is a shift in the standard climate conditions. Trend analysis disallows extrapolation of results beyond the start or end of the study period as long as the causes and interactions are unknown (Rapp 2000). In climate analysis, the classical component model of time-series is used for statistical trend analysis.

Most studies use linear trends to determine the magnitude of climatic changes, but climate trends do not have to be linear (Grieser et al. 2000; Trömel 2005). However, empirical studies showed that for time intervals ranging from some decades to a century this might usually be assumed (Schönwiese and Janoschitz 2005). Another problem with linear regression is that it assumes normal distributed data, which generally is not true for precipitation. Trömel (2005) developed a method that accounts for that problem and a comparison to the common method showed that in case of non-normal distributed data, linear tends to overestimate the trends (Schönwiese and Janoschitz 2005). Still, linear trends are widely used in climate science, also in this study. Using the same methodology makes it easier to compare the result of different regions.

4.1 Time Series Theory

A time-series y_t (y: property value, t: time) is an ordered sequence of observations of a parameter (Schlittgen and Streitberg 1995). This component model assumes that the time series emerges from the coactions of several temporal variation components and thus decomposition into those components is possible. It is assumed in climate analysis that those components are 1) mean of the time series M, 2) trend T, 3) cyclic component C (related to cycles continuing for several years, 4) seasonal component S, 5) extreme events E and 6) residual R (stochastic short-term variability, e.g. Rapp 2000). Those six components add up to the time series y_t:

$$y_t = M + T + C + S + E + R$$

As precipitation has a high natural variability, changes in time series may be visualized by smoothing that eliminates irregular variations by local approximation. Various approaches for detecting and quantifying the trend within a time series exist including linear regression, Gaussian low-pass filters, temporally moving averages and the difference of time-series averages (Rapp 2000).

4.2 Calculation of Trends

Different approaches of calculating trends used within this study are described in the following paragraphs. The simplest approach is the calculation of the **difference of means** of two time series segments:

$$\Delta\overline{y} = \overline{y}_2 - \overline{y}_1 = \frac{2}{N}\left(\sum_{t=\frac{N}{2}+1}^{N} y_t - \sum_{t=1}^{\frac{N}{2}} y_t\right)$$, with N = number of time series values.

Rapp (2000) recommends using time series segments of equal length to include all time series values with the same weight. Furthermore, those two segments should not overlap and cover the whole analysis period. If the number of time series values is uneven, the central property value is used for the calculation of both means.

Linear trends may be calculated using simple **linear regression**. It determines an explicit functional relationship that is described in a relation equation. A straight line is drawn through the time series y_t of length N (Schönwiese 1992):

$$\hat{y}_n = \alpha + \beta \cdot t_n,$$

with the ordinate values of the regression line $\hat{y}_n$ at the times t_n and the regression coefficients α and β. The regression equation is calculated using the “least square method” that minimises the quadratic deviations of the original data from the regression line (Schönwiese 1992; Rapp 2000):

$$\sum_{n=1}^{N} \left(y_n - \hat{y}_n\right)^2 = Min\,.$$

The input variables of the regression model are treated as independent variables and the slope β of the regression line is calculated by (Schönwiese 1992):

$$\beta = \frac{\frac{1}{N}\sum_{n=1}^{N} t_n y_n - \frac{1}{N}\sum_{n=1}^{N} t_n \frac{1}{N}\sum_{n=1}^{N} y_n}{\frac{1}{N}\sum_{n=1}^{N} t_n^2 - \left(\frac{1}{N}\sum_{n=1}^{N} t_n\right)^2}$$

There are different ways to indicate the trend T (Rapp 2000):

(1) mere information about trend direction: $T = \operatorname{sgn}\beta$,

(2) absolute trend calculating the difference of the first and last ordinate value of the regression line for the studied timeframe: $T = \Delta\hat{y} = \hat{y}_N - \hat{y}_1 = \beta(N-1)$, with the number of time series values N (t_n = 1,...,N),

(3) standardized trend: $T = \frac{\Delta\hat{y}}{N}k$, for a period of k = 1, 10, 50 or 100 years,

(4) relative trend: $T = \frac{\Delta\hat{y}}{\bar{y}}$ or $T = \frac{\Delta\hat{y}}{\hat{y}_1}$, respectively.

Using standardized trends might be problematic, when k is much longer than the studied period, because it misleads to an extrapolation of trends beyond the observation period. Standardized trends proved valuable, if single time series that should remain in the analysis, have marginally smaller temporal data availability than the bulk of data series. The advantage of relative tends is that they allow comparison of data series with spatially varying averages. While absolute trends reflect small-scale geographical dependencies, relative trends better illustrate larger-scale climatological structures (Rapp 2000).

Linear regression assumes normal distributed data and linear trends – an assumption daily and monthly precipitation data typically do not satisfy. Therefore, the non-parametric **Mann-Kendall trend test** developed by Mann (1945) and modified by Kendall (1970) is performed. This trend test does not assume linear trends. The test value Q_s is calculated by counting the algebraic signs of all possible differences of time series values (y) and relating the sum S to the number all possible combinations of time series values for $i < j$:

$$Q_s = \frac{\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\operatorname{sgn}(y_j - y_i)}{\frac{1}{2}N(N-1)} = \frac{S}{\frac{1}{2}N(N-1)}$$

For a number of time series values $N > 10$, the test value Q_s follows approximately a normal distribution with the mean μ = 0 and the variance $\sigma^2 = \frac{2(2N+5)}{9N(N-1)}$.

The trend Q is calculated by standardizing the test value Q_s:

$$Q = \frac{Q_s - \mu}{\sigma} = \frac{S}{\sqrt{\frac{1}{18}N(N-1)(2N+5)}}$$

For identical time series values, KENDALL (1970) modified the test:

$$Q = \frac{S}{\sqrt{\frac{1}{18}\left[N(N-1)(2N+5) - \sum_l (b_l - 1)(2b_l + 5)\right]}},$$

with b_l as the number of identical time series values of ordinate value y_l (Rapp 2000).

4.3 Significance, Spatial and Temporal Representativeness of Trends

As climate is highly variable in time and space, climate changes cannot be confirmed using single data series. Significant developments have to be temporarily stable and to occur area-wide (Rapp 2000). This is studied by assessing, besides the significance of trends, their spatial and temporal representativeness. Note that there is a difference in the representativeness of trends and of the climate element itself. Temperature, for instance, shows a higher spatial representativeness than precipitation, which has not necessarily to be true for connected trends.

The **significance** of trends is assessed using the non-parametric Mann-Kendall trend test. For the test values Q (for calculation procedure, refer to section 4.2) the confidence limits V and probability values α of normal distribution listed in Table 4.1 are valid. The significance estimation used in this study follows the one suggested by the KLIWA project (KLIWA 2000). Information on the significance of trends is completed by evaluating the spatial and temporal representativeness of trends.

Table 4.1: Significance of Mann-Kendall trend test value Q by specifying the confidence limits C and the probability values α for a standard normal distributed test statistics (KLIWA 2000; Rapp 2000)

Significance calculation	Q	C	α
low significance	> 1,282	> 80%	< 0,2
	> 1,645	> 90%	< 0,1
likely significant	> 1,960	> 95%	< 0,05
	> 2,576	> 99%	< 0,01
very likely significant	> 3,290	> 99,9%	< 0,001

Temporal Representativeness refers to variations in the trend values, when the study period is being shifted gradually (Rapp 2000). It may be studied by calculating and comparing the trends of many time-series subintervals. Generally, the significance of a trend increases with decreasing variations superposing the trend. Thus, relatively high or low values at the beginning or end of a time series have particularly high influence, primarily on linear trends and may distort them (Schönwiese and Janoschitz 2005). This source of error may be countered by successively shifting the analysis period. In this study, such kind of temporal-shifting analysis was used for 30-year-trends to assess the temporal representativeness of trends. Schönwiese and Janoschitz (2005) showed that trends tend to become unstable for time series shorter than 30 years. They concluded that trend calculation should be done for time series with a length of at least 30 years, 50- to 100-year trends are considered as relatively secure.

Spatial Representativeness accounts for the magnitude of trend variations from place to place. Surface air temperature generally shows a higher spatial representativeness with a lower decrease at increasing distance than precipitation (Rapp 2000). The spatial representativeness is studied by correlation analysis and comparing the trends of different stations and regions. Spatial representativeness is measured by the two-dimensional linear Pearson product moment correlation coefficient r that describes the similarity of time series or characteristic parameters of two stations (Rapp 2000). The coefficient of determination r^2 is the absolute value of the variance of both time series (Schönwiese 1992). A correlation coefficient of $r = 0.7$ and accordingly an explained variance of 50% are the minimum criteria for sufficient spatial representativeness (Rapp 2000).

4.4 Statistical Tests

Significant differences in the means $\overline{y_1}$ and $\overline{y_2}$ of two independent, non-overlapping time series segments of length N_1 and N_2, may be evaluated using the **t-test**. The sub-intervals should be of the same length ($N_1 = N_2$) as departures from normal distribution are then less severe (Rapp, 2000). For $N_1 = N_2$ the test statistic $\hat{t}$ is calculated by:

$$\hat{t} = \frac{\left|\overline{y_1} - \overline{y_2}\right|}{\sqrt{\frac{\sigma_1^{\ 2} + \sigma_2^{\ 2}}{N_1}}}, \text{ and the degree of freedom } \upsilon \text{ by: } \nu = \frac{(N_1 - 1)\left(\sigma_1^{\ 2} + \sigma_2^{\ 2}\right)}{\left(\sigma_1^{\ 2}\right)^2 + \left(\sigma_2^{\ 2}\right)^2}.$$

The test statistic is compared to tabulated values of the t-distribution. Sachs (1993) states that the t-test is robust against deviations from normal distribution for $N_1 = N_2 > 10$, just for considerably askew distributions of similar shape N should be above 20.

Analogue to the parametric t-test the non-parametric **Mann-Whitney (Wilcoxon) U-test** is used to compare two unrelated samples of quantitative character. The test statistic U is calculated from the ranks of the samples:

$$U = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1$$

with the sample sizes n_1 and n_2 and the summed ranks R_1 of sample 1.

Statistic significant differences in the variance of two samples of different populations are controlled by using the **F-test**. The F-value is calculated by dividing the estimated variances ($\hat{\sigma}_1, \hat{\sigma}_2$) of both samples:

$$F = \frac{\hat{\sigma}_1^{\,2}}{\hat{\sigma}_2^{\,2}}.$$

The **Kolmogorov-Smirnov test** (KS-Test) is used to detect significant differences in the probability density functions of two samples. As it is a non-parametric and distribution free test, it does not make any assumption about the distribution of the data. The KS-test is sensitive towards changes in location as well as shape of the empirical cumulative distribution functions of both samples. The empirical distribution function F_n for n observations y_i is calculated using the following formula:

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} \begin{cases} 1 & \text{for } y_i \le x, \\ 0 & \text{otherwise.} \end{cases}$$

The Kolmogorov-Smirnov test statistic is given by:

$$D_n^+ = \max(F_n(x) - F(x)),\ D_n^- = \max(F(x) - F_n(x)),$$

with $F(x)$ being the empirical distribution function of the second sample.

4.5 Possible Sources of Error

There are numerous potential sources of error in trend analysis. Any trend of climatological time series is more or less afflicted with flaws (Rapp 2000). A differentiation is made between systematic (corrigible) and non-systematic (random) errors. Known sources of error might be overcome by correction approaches, whereas unknown sources of error have at least to be taken into account when interpreting the results (Rapp 2000).

Systematic errors occur for instance when measuring precipitation. Such systematic deviations from the true value are primarily due to wind errors (over-and out-blowing of precipitation). Other sources of error relate to design and characteristics of the gauge, device defects and monitoring errors (Sevruk and Nespor 1994). Strong wind leads to about 10% lower rainfall amounts detected by the Hellmann rain gauges. For solid precipitation like snow the deficits are even higher – more than 50% are possible (Goodison et al. 1998). Another source of error in precipitation measurements are evaporation and moistening errors. Richter (1995) found that those are about 3% in the lowlands and might be twice as much in the low mountain ranges. For precipitation trend analysis a correction of precipitation totals is not necessary as the use of corrected precipitation values does not significantly influence the trends, whereas for analysis that focus on absolute precipitation totals like water balance studies correcting precipitation totals is essential (Bernhofer et al. 2002).

Data gaps might strongly influence the calculated trends, depending on 1) the timing of the gaps within the time-series, 2) the extent of the gaps, and 3) the time series characteristics such as length, variability and trend. Rapp (2000) showed that gaps at the tails have larger influences on trends compared to those in the midst. Furthermore, the chance of distorting the trend increases with the number of consecutive data gaps and with increasing time-series variability. When investigating trends of extremes missing data have even a stronger influence, as extremes might have been missed (Manton et al. 2001). Schönwiese and Rapp (1997) demand 90% data availability for executing reasonable trend analysis.

Inhomogeneities in time series might strongly distort existing trends or pretend a trend where none is existent. An inhomogeneity exists if none-meteorological causes produce variances in the statistical characteristics in climatological time series (e.g., Schönwiese and Janoschitz 2005). Such causes might be aging effect of measuring devices, inconsistencies in the observation practices, erroneous working instruments as well as changes in 1) station location, 2) measuring devices, and 3) local station surroundings (Gisler et al. 1997). For instance the improvement in precipitation gauges may lead to apparently higher precipitation. This bias can produce artificial trends in analysis of changes in precipitation extremes, particularly in analysis of light rainfall or snowfall (Nicholls and Murray 1999). Differences in the time series of nearby stations may indicate inhomogeneities, as long as not all stations are affected by the same inhomogeneity. Inhomogeneities might express themselves in gradual or abrupt changes.

Homogeneity tests have been developed for detecting such artificial abrupt or gradual changes. Correction of inhomogeneous data series is possible by different homogenisation approaches. Such a homogenisation transfers information from the reference data series to the time series that needs to be homogenized. This is not reasonable for time series analysis since no new spatial information is derived from such an approach (Rapp 2000). Bernhofer and Goldberg (2001) note that homogenisation should be used in a conservative manner to avoid tampering the time series for later analysis. Homogeneity analysis should rather be a method to evaluate time series than an approach to „straighten“ them. Within the CLISAX project (Statistical Assessment of Regional **Cli**mate Trends in **Sax**ony; Bernhofer and Goldberg 2001), the data of which are used within this study, different homogeneity tests (e.g., the numerical approaches Abbe-, Buishand- and Alexanderson-test and some graphical approaches) were applied.

5 Study Area and Data Base

The study area mainly comprises the German Free State Saxony and parts of surrounding federal states within Germany. It is situated in Central Eastern Germany in Central Europe (Figure 5.1). A short characterisation of Saxony's climate is given, before Saxon climate changes are discussed. Saxony's climate is affected stronger by continental influences, compared to other German regions, as the continental influence increases, when going eastward within Germany.

Figure 5.1: Map of Europe with situation of the German Free State Saxony

5.1 Climatic Characteristics of Saxony

Saxony may be categorized in three climate districts: 1) German low mountain range climate (Erzgebirge, Vogtland), 2) German highland and hill country climate (Erzgebirge foreland, Elbe Sandstone Mountains), 3) East German inland climate (lowlands around Leipzig, Lausitz, Elbe valley; SMUL 2005). The summer temperatures in Saxony's lowlands are comparable to those of the mild southwest of Germany due to larger continental influences.

The climatic characteristics of Saxony are to a large extent dominated by the Erzgebirge and other southern and western mountains namely Elbe Sandstone Mountains, Thuringian Mountains, Fichtelgebirge and Harz that inhibit the access of southern and western air masses to Saxony (Goldschmidt 1950). Only northern and eastern air masses can access Saxony almost unhampered, but those air masses are rarely connected with considerable precipitation. The highest precipitation totals are related to local convective summer rainfall (thunderstorms) and western and north-western weather fronts, blocked partly by the upstream mountains (Goldschmidt 1950). This explains Saxony's low precipitation totals compared to other German areas.

Foehn effects may occur at the Erzgebirge during south-western wind directions leading to higher temperatures and reduced precipitation north of the Erzgebirge (SMUL 2005). The high frequency of north-west winds in summer and connected luv-effects on the north side of the Erzgebirge result in an increase of the summerly precipitation maximum (summer precipitation type of climate) compared to other East German low mountain ranges like Harz and Thuringian Mountains, where winter precipitation maxima occur (winter precipitation type of climate; SMUL 2005). However, the contribution of winter precipitation to total precipitation is rising with increasing altitude (Goldschmidt 1950).

Seasonal precipitation variations are lower in the mountains than in the lowlands. In the first half of the 20th century the number of precipitation days is particularly low in September at all altitudes and high-pressure weather conditions typically for March are also related to major dryness (Goldschmidt 1950). March has changed its character in the second half of the 20th century and is not particularly anticyclonal anymore. The seasonal distribution of precipitation is not ideal for the agricultural sector, since the most efficient precipitation normally falls in the harvest time (particularly in the low altitudes) and not in spring when vegetation emerges.

5.2 Data Base

Regional extreme precipitation and drought analysis with high spatial resolution was done for Saxony and surrounding areas based on 130 stations with monthly and 113 stations with daily precipitation data (Annex 1). Figure 5.2 displays the situation of those 130 stations and their attribution to the nine regions described in section 5.5.

The core study period is 1951—2000. Additional analysis with a reduced data coverage are done for the periods 1901—2000 (monthly data only), 1931—2000 and 1941—2000. For every analysis period, the same analyses were done for the records until 2006. The influence of this extension of the study period by six years on the results of the trend analysis was studied for most of the investigations.

The availability of monthly and daily precipitation time series is best for timeframe 1951—2000 (Figure 5.3). Before 1951 nearly undisturbed data series are available for just a few stations and also after 2000 the data coverage is declining again.

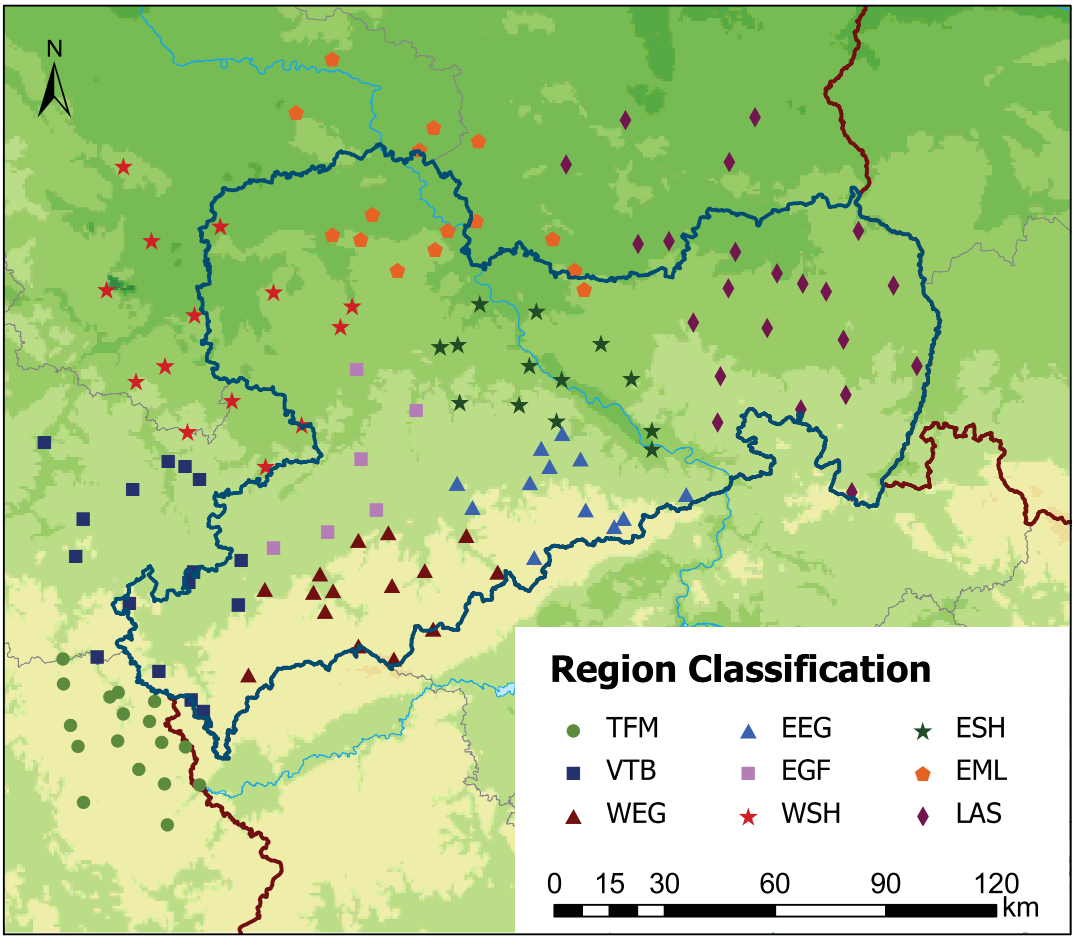


Figure 5.2: Map of the rain gauge and climate stations with regional classification

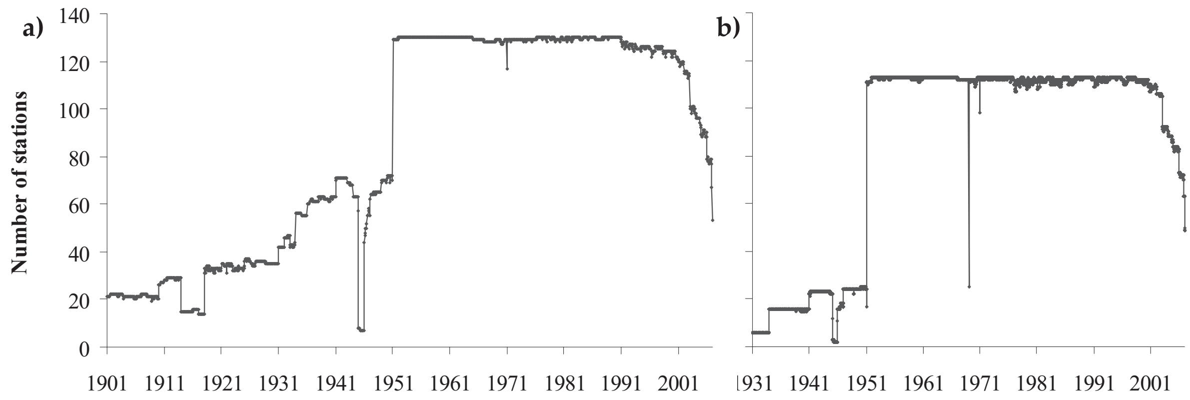


Figure 5.3: Availability of a) monthly and b) daily precipitation time series for 1901 to 2006

The precipitation records used within this study are taken from the Saxon climate database, which was developed within the project CLISAX for the Saxon State Agency for Environment and Geology (Bernhofer and Goldberg 2001; Bernhofer et al. 2001, 2002). Bernhofer et al. (2001) note that the data assimilated into the Saxon climate database were generally raw data with insufficient corrections of inhomogeneities. Therefore, comprehensive data verification was performed within the CLISAX project, and selected records were already analysed regarding their homogeneity (Annex 1). Nevertheless, some errors most probably remained in the data series (Bernhofer et al. 2001). Although the data were checked again, not all errors may be excluded. Some errors are known, but impossible to erase, others might still be unknown (section 5.3).

5.3 Data Quality

Ensuring the quality of data is a very important part in reliable climate trend analysis results. Nevertheless, there are several sources of errors in the data and not all errors may be eliminated. Therefore, the main focus of this work is on general trend directions and averaged regional trends and not on the absolute magnitude of single station trends. This approach might yield more robust results compared to station trends for some errors, particularly the random ones, but not for systematic errors occurring in the majority of data series. Therefore, it is important to include the knowledge about systematic errors and their possible influences on the data series trends in the interpretation of trend analysis results. One of those systematic errors in the precipitation data series is the change in the systematic of attributing data to the measuring day. The change occurred at the turn of the year 1968/69 in the former German Democratic Republic and 1970/71 in the Federal Republic of Germany (Bernhofer et al. 2001). Due to this change, the values of December 31st 1968 and 1970, respectively, are missing at most stations.

Bernhofer and Goldberg (2001) noticed discrepancies between the monthly precipitation totals provided by the German Weather Survey (DWD), the monthly values of year books and values summed up from daily data. In most cases those discrepancies are probably due to the described change in the systematic of attributing precipitation data to the measuring day and occur only prior 1968 and 1970, respectively. For the station Leipzig those discrepancies are demonstrated for the years 1951/52 and 1968/69 (Table 5.1).

Large differences in the monthly precipitation totals can be explained using the daily data in many cases. For instance, the daily precipitation values of April 30th (5.7 mm) and August 31st (25.1 mm) in 1951 have apparently been attributed to May and September in the monthly precipitation time series taken from the Saxon climate database. Sometimes, particularly at the beginning of the records, monthly values were rounded for selected stations, causing minor discrepancies in the time series (Table 5.1). After 1968, there are no major discrepancies in the monthly precipitation records derived from daily data and the ones from the Saxon climate database at station Leipzig. This is true for the majority of analysed stations.

Depending on the precipitation total of the last day per month the differences between the monthly precipitation time series taken from the Saxon climate database and the one derived from daily data can be quite high and may have a significant influence on the monthly as well as seasonal precipitation trends (Table 5.2). For the station Leipzig, the Mann-Kendall trends of June and Autumn are of low significance for the precipitation time series, derived from daily data, but non-significant for the monthly time series, taken from the Saxon climate database. Furthermore, the significance of the winter half year trends is higher for the time series from summed up daily data. Since the significance of trends is affected by the data used for the trend calculation and a homogeneous treatment for all data is not possible, all trends and not just the significant ones are incorporated in the regional trends and displayed in maps. Furthermore, this work focuses on the direction of trends and not on their absolute magnitude; as compared to the magnitude, the trend direction is more robust against small discrepancies in data series.

Since monthly data are available for a longer timeframe than daily data and to ensure an as far as possible consistent data base, this study uses monthly precipitation time series provided by the Saxon climate database (Bernhofer and Goldberg 2001) for monthly analysis and daily precipitation time series for daily analysis. Only in a few cases, where no monthly but only daily data were available, monthly precipitation values were summed up from daily data.

Table 5.1: Discrepancies in monthly data for the years 1951/52 and 1968/69 for station Leipzig-AWST

Date	Summed up from daily data Monthly totals	Annual totals	Monthly precipitation record (Saxon climate data base) Monthly totals	Annual totals	Difference	precipitation of the last day per month
01/1951	36.3		36.0		0.3	0.0
02/1951	29.9		30.0		-0.1	0.0
03/1951	46.2		46.0		0.2	0.4
04/1951	18.3		13.0		5.3	5.7
05/1951	62.3		68.0		-5.7	0.0
06/1951	108.1		108.0		0.1	0.0
07/1951	56.4		56.0		0.4	0.0
08/1951	41.6		17.0		24.6	25.1
09/1951	36.6		62.0		-25.4	0.0
10/1951	7.0		4.0		3.0	3.5
11/1951	81.1		84.0		-2.9	0.7
12/1951	22.1	**545.9**	22.0	**546.0**	0.1	1.3
01/1952	26.3		27.6		-1.3	0.0
02/1952	24.8		22.1		2.7	2.7
03/1952	67.7		66.3		1.4	4.1
04/1952	19.6		23.7		-4.1	0.0
05/1952	52.5		45.9		6.6	6.6
06/1952	52.4		59.0		-6.6	0.0
07/1952	16.7		16.7		0.0	0.0
08/1952	57.4		55.8		1.6	1.6
09/1952	153.2		154.7		-1.5	0.1
10/1952	59.4		59.5		-0.1	0.0
11/1952	73.8		70.6		3.2	3.2
12/1952	23.0	**626.8**	26.2	**628.1**	-3.2	0.0
…						
01/1968	61.8		61.8		0.0	0.0
02/1968	35.9		35.9		0.0	0.0
03/1968	33.3		32.3		1.0	1.0
04/1968	29.5		30.5		-1.0	0.0
05/1968	35.4		35.4		0.0	0.0
06/1968	42.1		42.1		0.0	0.0
07/1968	34.5		34.5		0.0	0.0
08/1968	47.7		33.3		14.4	14.4
09/1968	79.7		80.4		-0.7	13.7
10/1968	33.4		47.1		-13.7	0.0
11/1968	47.9		47.9		0.0	0.0
12/1968	21.4	**502.6**	21.4	**502.6**	0.0	0.0
01/1969	51.5		51.5		0.0	0.1
02/1969	39.3		39.3		0.0	0.0
03/1969	34.2		34.2		0.0	3.9
04/1969	66.4		66.4		0.0	1.6
05/1969	74.2		74.2		0.0	1.5
06/1969	76.3		76.3		0.0	0.0
07/1969	11.5		11.5		0.0	0.0
08/1969	69.5		69.5		0.0	0.0
09/1969	33.8		33.8		0.0	0.0
10/1969	18.1		18.1		0.0	0.9
11/1969	28.3		28.3		0.0	0.0
12/1969	27.5	**530.6**	27.5	**530.6**	0.0	0.2

The homogeneity of the used data series, particularly those of daily data, cannot be assured for all stations. Non-homogenous data series within the Saxon climate database were not homogenized without knowing the sources of inhomogeneities (Bernhofer and Goldberg 2001), because changing a time series with the values of another time series is regarded to be critical and does not give additional information for trend analysis (Rapp 2000). Figure 5.4 gives an overview about the homogeneity status of the time series used within this study, according to the Saxon climate database. More than half of the stations were tested for homogeneity. Out of those, 70% are classified as homogenous with a high probability. Less than 10% of the tested stations had major inhomogeneities that demanded the application of homogenisation procedures. Overlaying this map of homogeneity classes with the individual trend maps delivers information about the possible influence of inhomogeneous data on the general trends.

Table 5.2: Influence of the chosen monthly precipitation time series (R_M(mon): monthly totals from Saxon climate database, R_M(day): summed up from daily data) on the trends (relative linear trends and nonparametric, non-linear Mann-Kendall trends) and their significance for station Leipzig, timeframe 1951—2000

	Relative linear trend [%]		Mann-Kendall trend			
	R_M(mon)	R_M(day)	R_M(mon)		R_M(day)	
Jan	6.7	7.1	0.335		0.418	
Feb	25.8	28.1	0.837		0.887	
Mar	39.7	39.6	1.113		1.054	
Apr	20.1	21.7	0.653		0.535	
May	-19.1	-16.7	-0.870		-0.686	
Jun	-28.1	-30.6	-1.179		-1.372	+
Jul	5.9	7.6	0.862		0.887	
Aug	19.4	13.5	0.410		0.134	
Sep	7.2	13.3	0.519		0.853	
Oct	-12.4	-6.1	-0.109		0.184	
Nov	37.8	37.9	1.882	*	1.857	*
Dec	39.0	33.7	1.440	+	1.422	+
Spring	11.3	12.8	0.644		0.736	
Summer	-1.3	-3.5	0.619		0.368	
Autumn	10.8	15.3	1.021		1.355	+
Winter	24.5	26.1	1.353	+	1.508	+
SHY	0.1	0.2	0.000		0.033	
WHY	24.6	26.6	1.784	*	2.008	**
Annual	8.6	9.9	1.021		1.171	

level of significance + $\alpha < 0.2$ * $\alpha < 0.1$ ** $\alpha < 0.05$ *** $\alpha < 0.01$

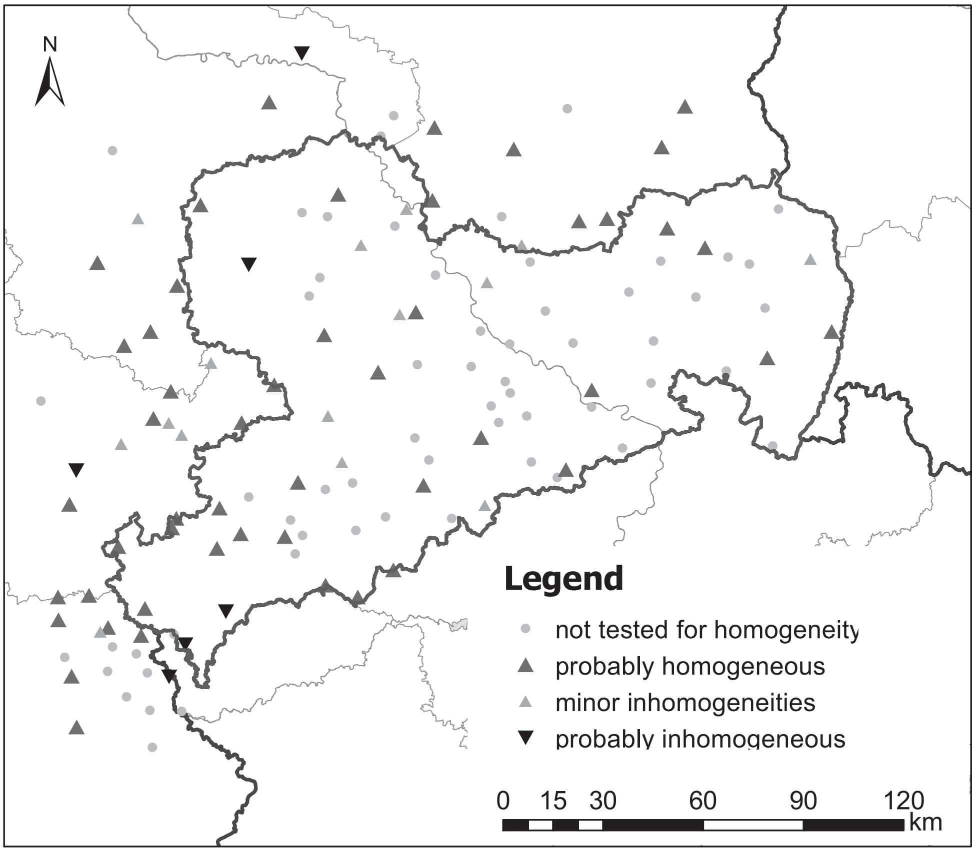


Figure 5.4: Map of the homogeneity status of the rain gauge stations

A source of inhomogeneity in Saxon precipitation time series is the change in instrumentation in 1933/34 with the introduction of the Hellmann rain gauge (type 1886, Antonik and Pelzl 1952). Prior to 1933, devices with 500 or 1000 cm² collecting area (after Bruhns and Schreiber, respectively) were in operational use. Those devices collected about 10% more precipitation than the Hellmann rain gauge with its 200 cm² collecting area (Antonik and Pelzl 1952; Goldschmidt 1950; Tremmel and Stellmacher 1985). Since the earliest daily precipitation time series analysed, start in 1931, this inhomogeneity should not affect the trend results of daily extreme precipitation indicators. For monthly indicator time series prior 1934, this change in instrumentation might bias the trend results towards drier conditions in recent times.

5.4 Spatial Representativeness

The spatial representativeness of monthly precipitation time series is measured by the two-dimensional linear Pearson product moment correlation coefficient. Spatial representativeness is given for correlation coefficients $r \geq 0.7$. Generally the correlation coefficients of precipitation time series are declining rapidly with increasing distance, particularly in the first 200 kilometres. At higher distances the decline in variance is less rapid. Spatial representativeness in Germany is given up to a distance of about 100 to 200 kilometres, depending on the chosen month or season (Rapp 2000). In Saxony, the spatial representativeness is often below 100 kilometres, particularly in the mountainous southern part (Bernhofer et al. 2001).

Results of correlation analysis for 130 monthly precipitation time series for 1951 to 2000 give evidence for a limited spatial representativeness within the study area (Figure 5.5) in comparison to the results of Rapp (2000). Numerous correlation coefficients are below the threshold for spatial representativeness of r = 0.7, single ones even at low distances of about 50 kilometres. Nevertheless, most correlation coefficients indicate satisfactory similarities between the precipitation time series to a distance of about 100 kilometres.

The spatial representativeness of precipitation time series furthermore depends on the month or season investigated. Large differences in precipitation at small scales are mainly due to convective precipitation that is characteristic for summer. Precipitation bound to large scale atmospheric circulation accounts for high spatial representativeness occurring primarily in winter. The reduced spatial representativeness of Saxon precipitation time series compared to the German mean is most probably due to the intense orographic structure of Saxony leading the pronounced luv- and lee-effects.

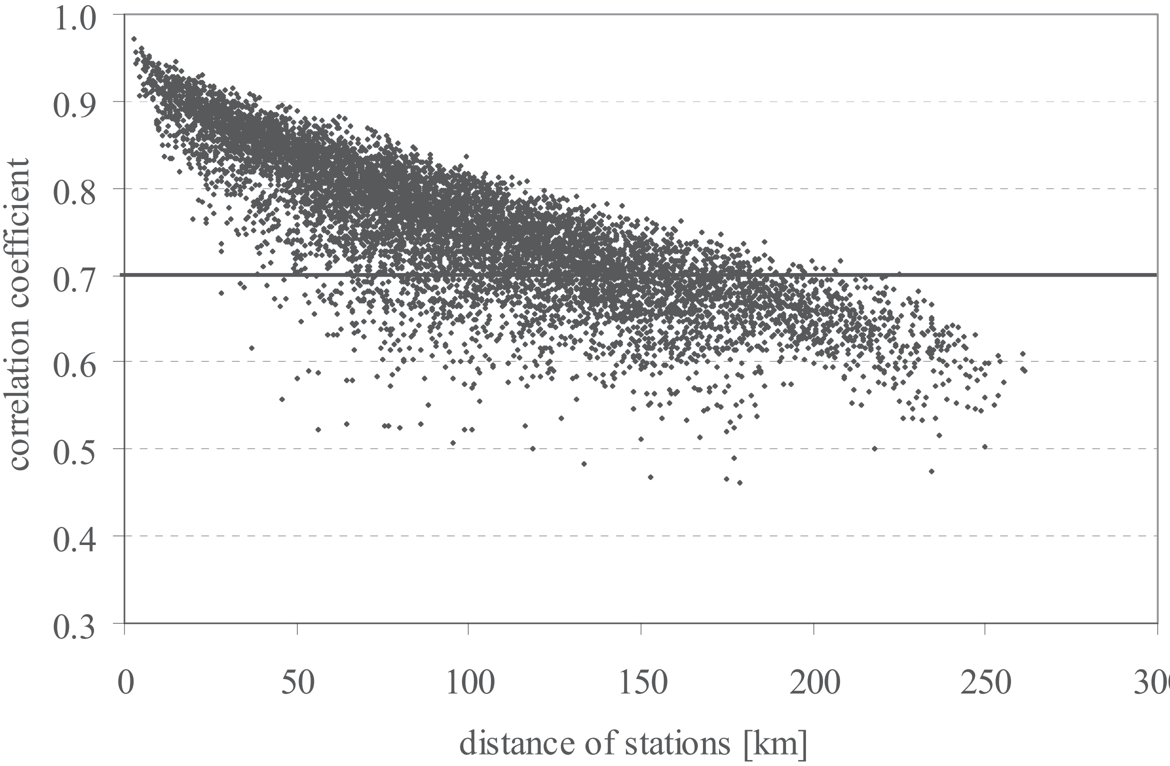


Figure 5.5: Dependence of Pearson correlation coefficient magnitudes of monthly precipitation totals on the distance of stations, timeframe 1951—2000

On a monthly basis spatial representativeness is highest for January, February, October and December and lowest for May, June and August (Figure 5.6, Annex 2). During the summer months, the spatial representativeness of precipitation is frequently below 50 kilometres, whereas it is generally above 100 kilometres in winter. Remarkably high correlation coefficients exist in October,

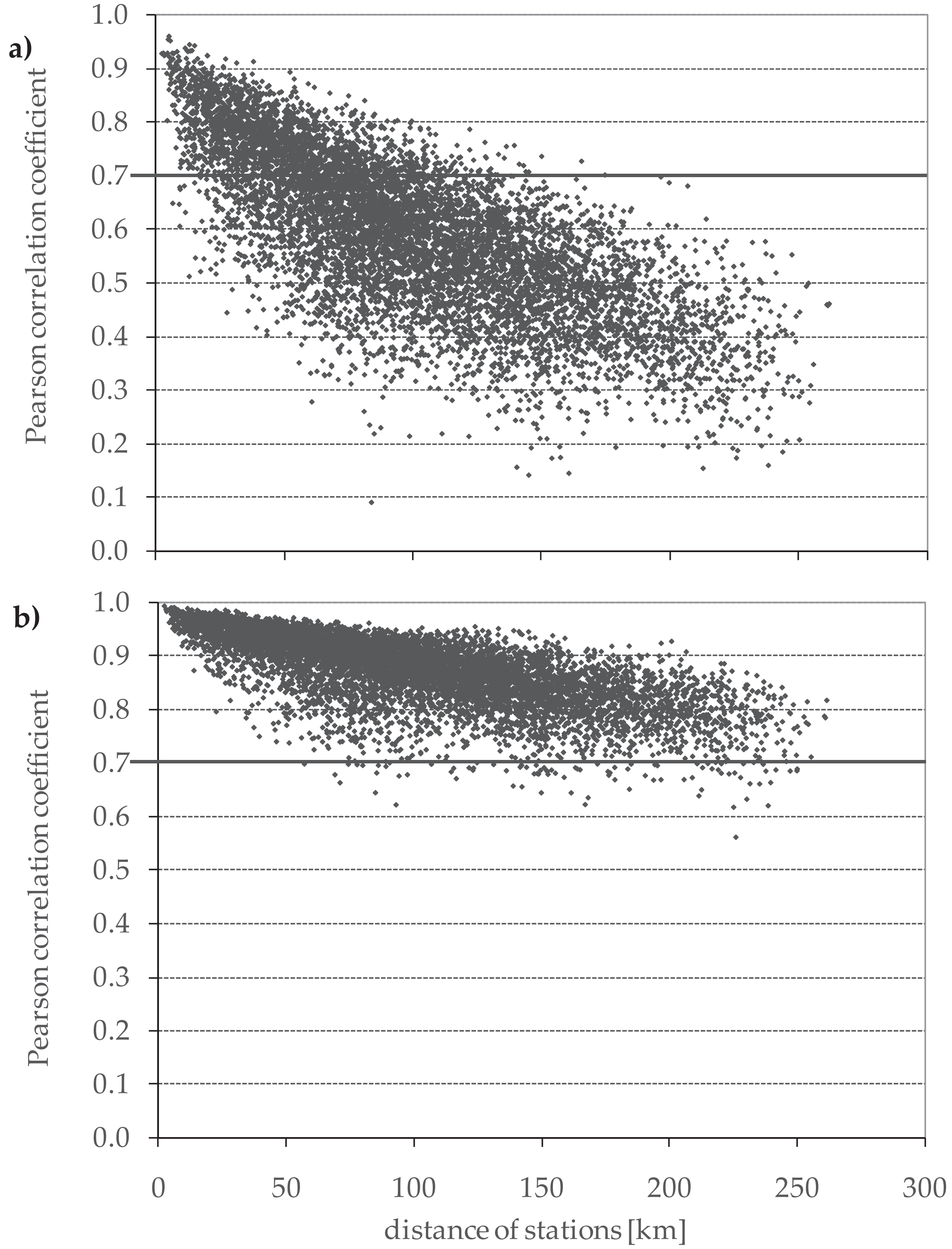


Figure 5.6: Dependence of Pearson correlation coefficient magnitudes of monthly precipitation totals on the distance of stations in the months a) August and b) October, timeframe 1951—2000

with a spatial representativeness of more than 250 kilometres. This month seems to be characterised by precipitation regimes that are to a very high degree bound to large scale precipitation pattern. Orography seems to have the lowest influence compared to other months, suggesting predominant northern or north-eastern wind directions. July sticks out amongst the summer months by comparably high correlation coefficients indicating either a lower percentage of convective precipitation or like in October a lower orographic influence due to the direction of precipitation fronts or both.

Spatial representativeness of precipitation data is required to unite single station trends into regional trends, which is one task of this study. Therefore, the results of correlation analysis are used to classify the rain gauge stations into regions with similar precipitation characteristics. The spatial representativeness within the regions is analysed in the next section for the complete monthly precipitation time series of 1951—2000 and for single months.

5.5 Regional Classification

As this study focuses on regional trends instead of single station trends a region classification of stations is necessary. This is done by attributing the stations to natural landscape units and by aggregating those units into larger regions with similar precipitation characteristics. This regional classification is supported by correlation and cluster analysis. Figure 5.7 displays the correlation matrix of the complete monthly precipitation time series of 1951—2000 in comparison to the distances of stations. The patterns generated by station distances are similar to those of correlation coefficients indicating that the magnitude of correlations depends to a high degree on the distance of stations (decreasing correlations with increasing distances; please refer to section 5.4). Altitude and wind direction are other important factors influencing correlation coefficients.

The region “Thuringian-Franconian Mountains” (TFM), situated south-west from Saxony (Figure 5.2) is most different from the other regions according to Pearson product moment correlation coefficients (Figure 5.7). Although the distances to the regions “Vogtland and Thuringian Basin” (VTB) and “Western Erzgebirge” (WEG) are quite low (partly less than 75 km) the connected correlations coefficients are comparably low, too. For the other regions the pattern of distance classes and correlation coefficient classes are more similar. Correlation coefficients greater than 0.9 normally refer to distances of less than 25 kilometres, correlation coefficient of 0.8 to 0.9 to distances of 25 to 75 kilometres and correlations of 0.7 to 0.8 to distances of 75 to 150 kilometres. Region VTB is most similar to region TFM as well as parts of regions WEG, EGF (Erzgebirge Foreland) and WSH (Western Saxon Hilly Country).

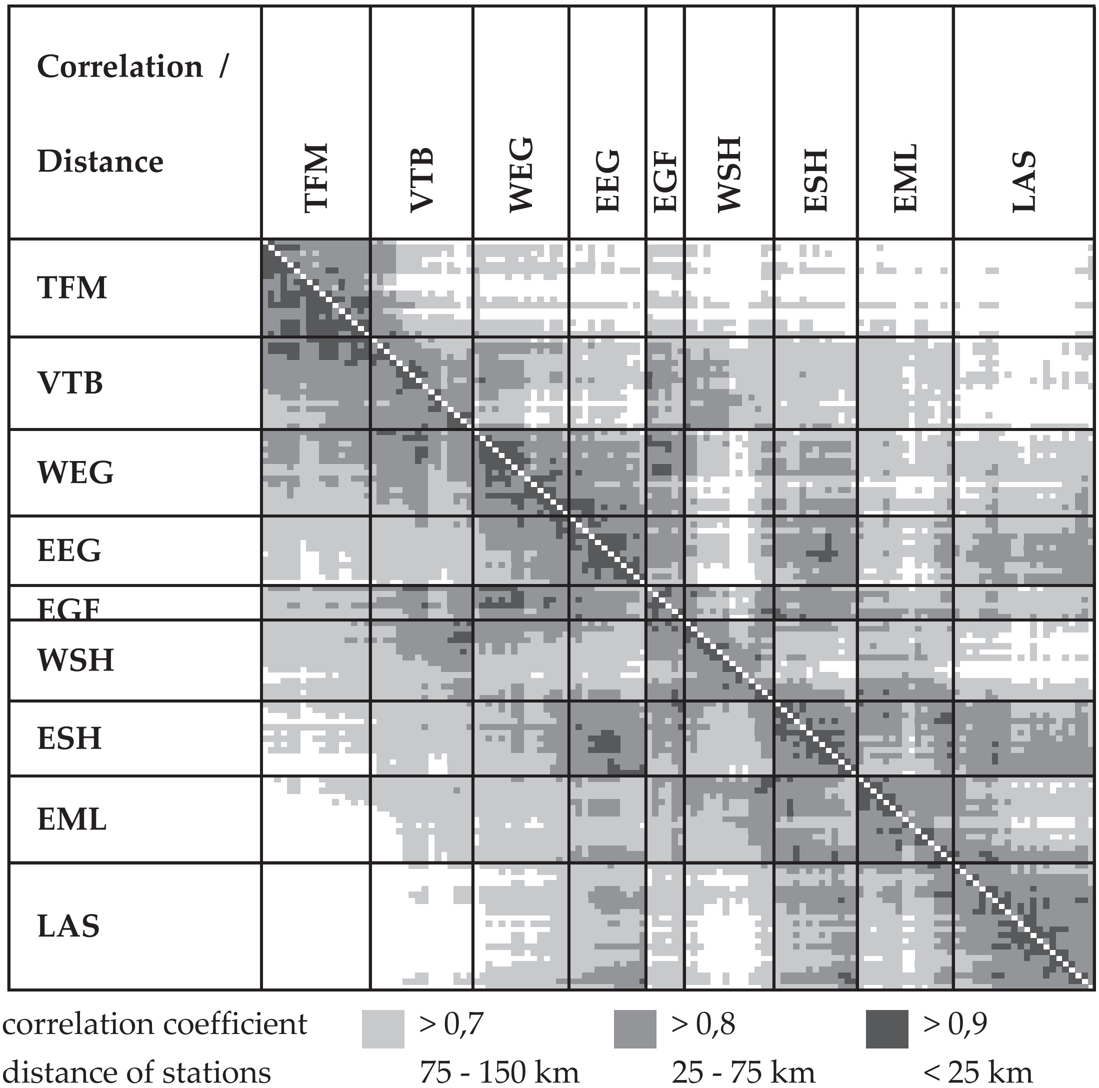


Figure 5.7: Matrix of Pearson product moment correlation coefficients of monthly precipitation time series for 1951—2000 (values above the "white line") compared to the distance of stations in kilometres (values below the "white line")

The three Erzgebirge regions (WEG, EEG and EGF) show high correlations among each other and for some analysis it seems possible to combine them to one large Erzgebirge region. Nevertheless, for some months like March, April, June and September there are distinguishable differences between those three regions (Annex 3), that led to the decision to treat them as single regions.

All Erzgebirge stations have greater correlation coefficients with stations of the "Eastern Saxon Hilly Country" (ESH) than with those of the "Western Saxon Hilly Country" (WSH). This might be due to the fact that region WSH is less influenced by luv-lee-effects of the Erzgebirge than region ESH, but more influenced by lee-effects of the Harz Mountains. The northernmost region of the study area, the "Elbe-Mulde Lowlands" (EML), shows the highest correlations with parts of the regions WSH, ESH and LAS (Lausitz and Spreewald). Region

LAS being the easternmost region is most similar to the "Eastern Erzgebirge" (EEG) and the "Eastern Saxon Hilly Country" (ESH).

All correlation coefficients suggest sufficient spatial representativeness over the whole year within the classified regions, since all values are above r = 0.7 (Figure 5.7). Based on this region classification regional analyses are done for a variety of extreme precipitation and drought indicators.

As expected, some stations have distinct similarities to neighbouring regions, particularly stations that are at the margins of a region. Those similarities appear differently in single months (Annex 3). Although slight changes in the region classification or an aggregation of regions to larger regions seem to be possible, the chosen classification has proven to be robust in all months. The correlation matrices for single months (Annex 3) support the classification, especially in the summer months June and August with their characteristic low correlations. In those months for most regions and in May for the regions VTB and WSH spatial representativeness is not given for a variety of stations within the regions. This might be critical for regional trend analysis and has to be checked again, when the results of station trend analysis are to be aggregated to regional trend information.

Table 5.3 shows the number of stations of each region for a total of 130 stations with monthly precipitation time series and for a total of 113 stations with daily precipitation time series. Most regions include about 15 stations. Just the "Erzgebirge Foreland" (EGF) contains considerably less station data and "Lausitz and Spreewald" (LAS) considerably more.

Table 5.3: Number of stations per region that is available for monthly and daily precipitation time series analysis

Region (Number/ Name/ Abbreviation)		Monthly time series	Daily time series
1/ Thuringian-Franconian Mountains	TFM	17	16
2/ Vogtland and Thuringian Basin	VTB	16	15
3/ Western Erzgebirge	WEG	15	13
4/ Eastern Erzgebirge	EEG	12	8
5/ Erzgebirge Foreland	EGF	6	5
6/ Western Saxon Hilly Country and Central German Black Earth Area	WSH	14	13
7/ Eastern Saxon Hilly Country	ESH	13	12
8/ Elbe-Mulde Lowlands	EML	15	12
9/ Lausitz and Spreewald	LAS	22	19
		130	**113**

6 Precipitation and Drought Characteristics of Saxony

Typical precipitation and drought conditions and patterns are to be characterised before conducting a detailed trend analysis of heavy precipitation and drought events in Saxony. The characterisation is mainly done on the basis of regional averages since analysing and discussing individual station data is too extensive and does not yield significant additional information. First, the regions are characterised regarding their monthly and seasonal precipitation averages. Next, the regional differences in the annual distribution of rainfall as well as the probability distributions of monthly precipitation totals are pointed out. Drought conditions and pattern as well as heavy precipitation events and wet periods are described using different indicators based on daily and monthly precipitation data.

6.1 General Characterisation of Precipitation Conditions

6.1.1 Average Precipitation Indices

Differences in regional precipitation totals mainly depend on altitude and the situation regarding mountain ridges that might block or accumulate precipitation from certain directions. Saxony is characterised by a distinctive orographic structure. Therefore, the regions analysed within this study are quite different regarding their natural landscapes, average altitudes and characteristic daily and monthly precipitation totals (Table 6.1). Altitudes of analysed stations range from 69 to 1213 metres and cover lowland to low mountain range climate regimes. In many regions, the range of altitudes is quite high. Most homogenous in respect to altitude are the regions TFM (Thuringian-Franconian Mountains) and EML (Elbe-Mulde Lowlands). According to their average altitude, the nine regions may be classified into four mountainous regions (TFM, VTB, WEG and EEG), three regions characterised by a predominant hilly countryside (WSH, ESH and LAS) and one lowland region (EML).

The region EGF (Erzgebirge Foreland) stands in between the mountainous and hilly regions showing characteristics of both. Annual precipitation averages range from about 500 mm (stations Neutz and Halle-Ammendorf in region WSH) to about 1100 mm (Fichtelberg/ WEG and Bischofsgrün/ TFM). Regional averages are in between this range with the lowest values of about 570 mm in the regions WSH (Western Saxon Hilly Country and Central German Black Earth Area) and EML and the highest average of 909 mm in region WEG (Western Erzgebirge; Table 6.1). In water shortage years, annual precipitation may be down to about 250 mm (50% of normal precipitation) at individual lowland stations and in water surplus years up to about 1700 mm (150% of normal precipitation) at mountainous stations.

Regarding daily precipitation maxima, region EEG (Eastern Erzgebirge) sticks outs by very high regional averages (Table 6.1). This is due to the extreme precipitation in August 2002 that affected this region and parts of region WEG and ESH (Eastern Saxon Hilly Country) most.

Table 6.2 shows the regional means and medians of precipitation for all months and seasons. Particularly for monthly data, the median values are considerably smaller than the means, indicating a skewed precipitation distribution that deviates from normal distribution. The departure of median from mean values is largest in March, July, September, October and December and lowest in February, June and November. For seasonal and annual data the deviation from normal distribution is much smaller.

Table 6.1: Regional averages of mean, minimum (min) and maximum (max) altitudes and precipitation totals (annual and daily) for 113 station with daily data available

	Altitude [m]			**Annual precipitation total 1951—2000 [mm]**			**Daily precipitation total 1951—2006 [mm]**		
Region	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Max**	**Max_{max}[1]**
1 / TFM	548	474	660	777	471	1085	2.1	79.6	94.5
2 / VTB	369	155	510	663	408	963	1.8	94.5	144.2
3 / WEG	557	391	1213	909	596	1334	2.5	119.3	178.8
4 / EEG	436	214	593	848	515	1254	2.3	193.2	267.3
5 / EGF	318	192	418	717	453	1020	2.0	100.5	120.0
6 / WSH	168	82	302	569	327	821	1.6	84.9	115.0
7 / ESH	176	110	290	628	392	909	1.7	134.4	228.2
8 / EML	104	76	155	571	348	798	1.6	102.8	130.8
9 / LAS	181	69	460	664	407	944	1.8	109.2	148.7

[1] Max_{max}: highest maximum daily precipitation value per region

Table 6.2: Average regional means (1st value) and medians (2nd value) of monthly, seasonal and annual precipitation totals for 113 stations, timeframe: 1951—2000

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS
Jan	61	42	69	61	48	35	41	39	46
	53	37	61	57	44	32	38	37	43
Feb	50	37	59	53	42	32	35	32	38
	44	35	57	52	40	30	35	32	38
Mar	54	44	68	64	51	38	42	40	45
	50	40	59	53	44	33	36	33	38
Apr	52	53	71	66	56	45	48	43	49
	50	47	64	59	51	41	43	38	47
May	65	64	78	74	64	55	57	51	61
	60	59	72	67	57	51	53	49	56
Jun	81	79	99	87	80	69	67	62	70
	78	75	94	84	76	64	65	58	68
Jul	86	81	108	105	88	68	79	64	80
	83	76	96	91	80	60	63	54	63
Aug	79	72	88	86	75	63	70	63	73
	74	66	82	78	70	57	59	59	67
Sep	60	51	69	63	57	45	50	45	52
	53	45	61	58	51	40	46	42	47
Oct	58	46	62	59	51	41	45	41	46
	50	38	51	49	44	35	37	46	37
Nov	58	45	64	61	49	39	44	42	48
	59	43	61	57	46	37	42	41	47
Dec	72	48	75	69	56	41	50	48	56
	63	44	68	59	47	37	45	43	50
Spr	171	162	217	204	172	138	148	134	155
	171	157	208	195	166	129	140	126	150
Sum	246	232	295	278	243	200	216	189	223
	245	227	288	270	232	192	204	185	211
Aut	176	142	195	183	158	125	138	128	146
	165	136	188	177	152	120	132	123	138
Win	184	128	204	184	146	108	127	120	141
	183	130	201	181	150	110	128	125	141
SHY	423	400	511	481	420	345	371	329	386
	424	398	504	472	414	343	370	324	379
WHY	356	264	398	369	299	227	258	243	280
	359	265	393	357	293	223	253	241	276
Ann	**777**	**663**	**909**	**848**	**717**	**569**	**628**	**571**	**664**
	776	**664**	**900**	**851**	**723**	**573**	**633**	**569**	**664**

On average, 246 dry, 119 wet and 91 rain days occurred in the study area (Table 6.3). In the mountainous regions (TFM, WEG and EEG) dry/wet days were less/more frequent than in the hilly country (WSH, ESH, LAS) or lowlands (EML). The regions EGF (Erzgebirge Foreland) and VTB (Vogtland and Thuringian Basin) stand in between. Per wet day on average 5.7 mm precipitation was falling. The share of wet day precipitation on total precipitation is about 97% in all regions, independent of the magnitude of wet day precipitation. Precipitation falling on days with more than 1 mm rainfall is highest in the mountainous southern regions (TFM, WEG, EEG) and lowest in the plane regions (WSH and EML) in the Northwest of the study area, like already described for annual precipitation totals.

As expected, the monthly and seasonal values vary in dependence of the annual precipitation cycle (sub-section 6.1.2). The simple daily precipitation index (SDPI) is highest during the summer months and season and lowest during winter in all regions (Annex 4). The highest regional SDPI of 8.6 mm d^{-1} has been observed for the Eastern Erzgebirge in July, and the lowest value of 3.5 mm d^{-1} for the 'Western Saxon Hilly Country' (WSH) in January and February and for the 'Elbe Mulde Lowlands' (EML) in February. Likewise, the share of wet day precipitation on total precipitation is highest in summer and lowest in winter. Between 92.7% (January, WSH) and 98.5% (July: VTB, WEG, EEG) of the monthly precipitation is falling on days with precipitation above 1 mm.

Table 6.3: Simple annual precipitation indicators averaged for nine regions (113 stations) for 1951—2000

Region	N-DD (Pd ≤ 1mm)	N-WD (Pd > 1mm)	N-RD (Pd ≥ 2mm)	SDPI [mm d^{-1}]	R-WD [mm]	R-WD [%]
1 / TFM	236	129	99	5.8	755	97.2
2 / VTB	248	118	87	5.4	639	96.3
3 / WEG	228	138	109	6.4	887	97.6
4 / EEG	233	132	103	6.2	826	97.4
5 / EGF	244	121	92	5.7	694	96.7
6 / WSH	260	105	77	5.2	546	96.1
7 / ESH	254	111	82	5.4	606	96.4
8 / EML	259	106	78	5.2	549	96.2
9 / LAS	249	116	87	5.5	642	96.6
	246	**119**	**91**	**5.7**	**683**	**96.7**

Abbreviations of individual indicators are explained in Table 2.5

6.1.2 Annual Precipitation Cycle

Saxony is characterised by a warm temperate climate with precipitation throughout the year. Nevertheless, it has a distinct seasonal climate with a pronounced summer maximum and a smaller winter maximum of monthly precipitation totals. The lowest monthly precipitation is generally to be expected in February and the largest in June to August.

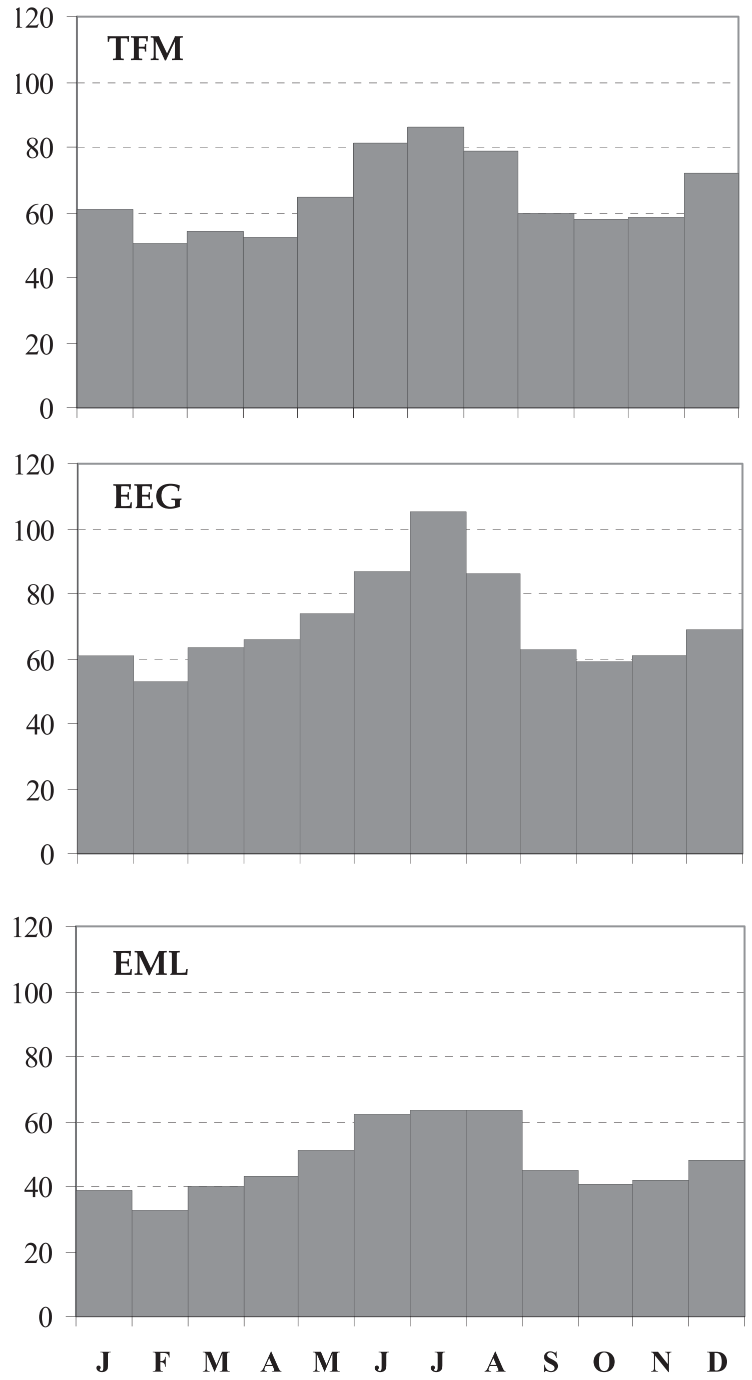


Figure 6.1: Annual precipitation cycle of the regions Thuringian-Franconian Mountains (TFM), Eastern Erzgebirge (EEG) and Elbe-Mulde Lowlands (EML); 1951—2000

The nine regions show quite similar annual precipitation cycles (Figure 6.1, Annex 5), although due to the different altitudes the magnitudes of monthly precipitation are differing by more than a factor of 1.5. Figure 6.1 shows the annual precipitation cycles of three example regions (TFM, EEG and EML). The annual precipitation cycle of most regions resembles the one of 'Eastern Erzgebirge' (EEG) most with a distinct summer precipitation maximum in July, a second smaller winter maximum in December and a distinct winter minimum in February. Only in the northern region EML (Elbe Mulde Lowlands) and in the 'Western Saxon Hilly Country' (WSH) the precipitation total of all summer months (June, July and August) is almost equal. For the 'Thuringian-Franconian Mountains' (TFM), the winter maximum in December is most pronounced and although it is still clearly smaller than the summer maximum the difference is less distinct than for the other regions. The autumn minimum of the annual precipitation cycle is quite similar over the months September, October and November. Just the precipitation totals of September are slightly higher than the ones of October and November in all regions.

6.1.3 Percentile Values of Daily and Monthly Precipitation

Percentile values of daily (Table 6.4) and monthly (Table 6.5) precipitation totals characterise the typical regional frequency distributions of precipitation. Two different calculation methods described in section 2.3 were used for computing the percentiles of daily precipitation time series. The percentiles were calculated for the normal period of 1961—1990, that is used as the reference period for trend calculations in chapter 0. The first method abbreviated with "ad" includes all non-missing days into the percentile-calculation, whereas the second method ("pd") only incorporates precipitation days ($R_d > 0$). Thus, the percentile-values of the second method are larger than those of the first method, which could result in different trends for the exceedance frequency of the same percentile value.

Due to the large percentage of days without any precipitation, the "ad"-method delivers zero values for the smaller percentiles – in some regions the percentiles are zero up to the median (50^{th} percentile). The 95^{th} percentile of the "ad"-method and the 90^{th} percentile of the "pd"-method approximately correspond to the 10-mm-threshold and the 99^{th}-percentile of the "ad"-method to the 20-mm-threshold. When including only days with precipitation ("pd") the 95^{th} percentile is about 15 mm high and the 99^{th} percentile has a magnitude of about 25 mm.

Regionally, the magnitude of the percentiles varies between the lowland regions and the mountainous (higher percentile values), as described in section

6.1 for average precipitation characteristics. This is also true for the percentiles of the monthly precipitation distribution (Table 6.5). The first percentile of the monthly precipitation distribution ranges from 4.7 mm in the lowlands (EML)

Table 6.4: Regionally and annually averaged percentiles of daily precipitation totals for 1961—1990 using two different calculation methods

	region	1st	5th	10th	50th	75th	90th	95th	99th
inclusion of all days (ad)	**TFM**	0.0	0.0	0.0	0.1	2.7	7.2	11.2	22.3
	VTB	0.0	0.0	0.0	0.1	2.0	5.8	9.5	20.1
	WEG	0.0	0.0	0.0	0.3	3.1	8.1	12.4	24.3
	EEG	0.0	0.0	0.0	0.2	2.7	7.4	11.7	23.8
	EGF	0.0	0.0	0.0	0.1	2.2	6.5	10.2	21.0
	WSH	0.0	0.0	0.0	0.0	1.6	5.1	8.3	18.0
	ESH	0.0	0.0	0.0	0.0	1.8	5.5	9.0	19.6
	EML	0.0	0.0	0.0	0.0	1.6	5.2	8.3	18.1
	LAS	0.0	0.0	0.0	0.0	2.0	5.9	9.4	20.0
days with precipitation only (pd)	**TFM**	0.1	0.2	0.3	2.4	5.7	10.8	15.4	27.2
	VTB	0.1	0.1	0.2	1.9	4.7	9.3	13.6	25.5
	WEG	0.1	0.2	0.3	2.6	6.2	11.8	16.6	29.7
	EEG	0.1	0.2	0.3	2.5	5.9	11.4	16.2	29.9
	EGF	0.1	0.1	0.2	2.1	5.1	10.0	14.3	26.7
	WSH	0.1	0.2	0.2	1.9	4.5	8.8	12.8	24.6
	ESH	0.1	0.1	0.2	2.0	4.7	9.3	13.4	25.7
	EML	0.1	0.2	0.2	1.9	4.6	8.8	12.6	24.0
	LAS	0.1	0.2	0.3	2.1	5.0	9.6	13.7	25.8

Table 6.5: Regionally and annually averaged percentiles of monthly precipitation totals for 1951—2000

Region	1st	5th	10th	50th	75th	90th	95th	99th
TFM	7.2	17.2	23.8	58.5	84.1	114.4	133.6	170.7
VTB	5.6	15.1	20.2	48.4	72.0	99.0	116.5	156.8
WEG	10.4	21.0	29.8	68.4	97.4	129.5	152.0	208.8
EEG	9.7	19.8	27.1	62.6	90.5	121.9	144.8	208.9
EGF	7.4	16.3	22.6	52.9	78.4	103.5	123.1	164.2
WSH	4.9	12.1	16.6	41.6	61.6	85.2	102.5	140.9
ESH	6.2	13.5	18.7	45.7	66.6	94.0	114.6	162.1
EML	4.7	11.5	16.3	42.2	62.3	83.8	102.1	142.3
LAS	6.7	14.8	19.7	48.3	70.6	97.4	120.0	172.1

to 10.4 mm in the mountains (WEG) and the 99th percentile varies from 142.3 (EML) to 208.9 (EEG). The values of the 50th percentile (median) correspond to the averaged monthly medians listed in Table 6.2 and are normally considerably smaller than the average precipitation means, also listed in Table 6.2. This discrepancy between mean and median values is due to the missing normal distribution of precipitation data. For daily precipitation data, the departure from normal distribution is much higher than for monthly data, resulting in median values close to zero.

Seasonal differences in the monthly precipitation distributions are displayed for the half years for the example regions TFM (Thuringian-Franconian Mountains) and ESH (Eastern Saxon Hilly Country) in Figure 6.2 and for the other regions in Annex 6.

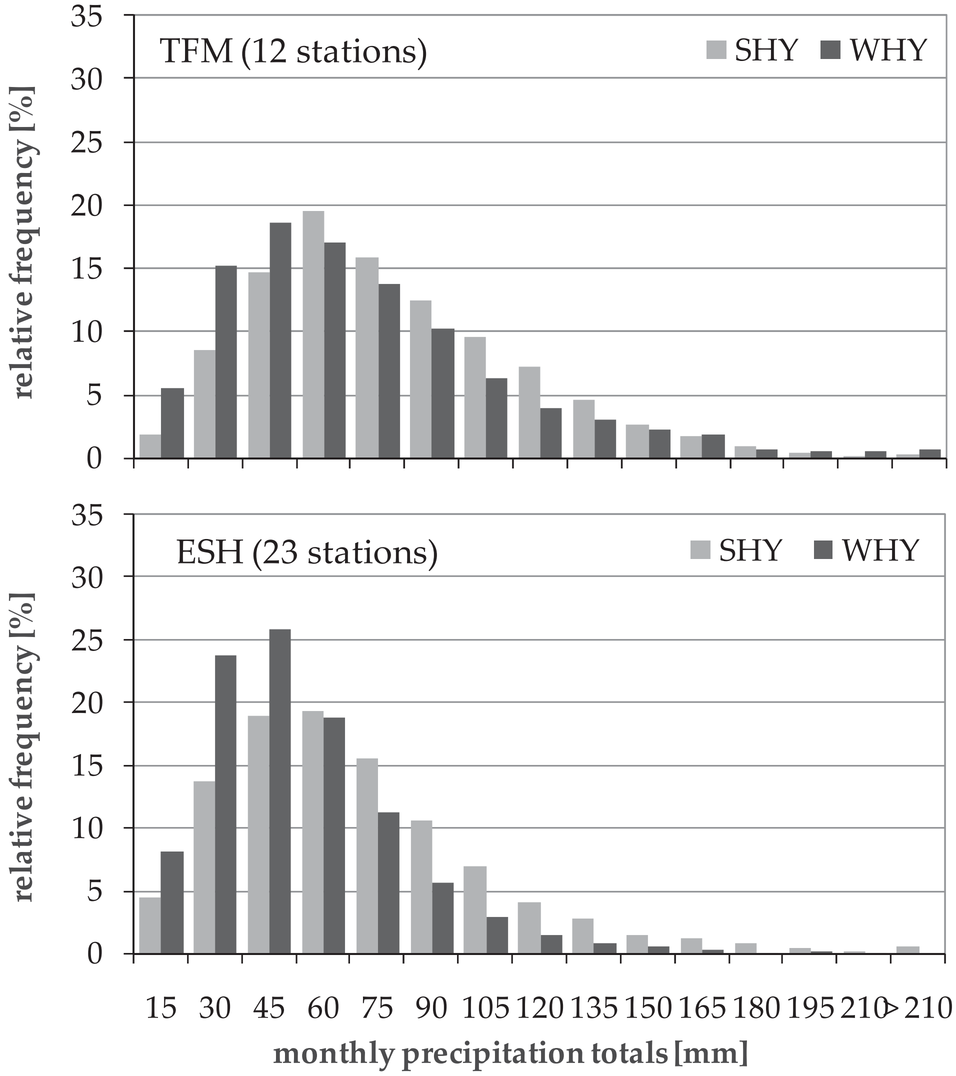


Figure 6.2: Histogram's of monthly precipitation totals for the summer (SHY) and winter (WHY) halves of the year for the regions TFM (Thuringian-Franconian Mountains) and ESH (Eastern Saxon Hilly Country) , timeframe 1951—2005

Generally the distribution of precipitation totals of the summer months is more expanded than the one of the winter months showing higher frequencies in lower classes during winter than compared to summer (Annex 6 and Figure 6.2). High precipitation classes occur considerably more frequent during summer. The differences between the histograms of the half years are smallest for the mountainous regions TFM, WEG and EEG. The frequency within the most frequently occupied class is almost the same for both half years, although the maximum of the winter half year distribution is reached one class below the one of the summer half year. In contrast, the rate of recurrence in the class of highest occurrence of monthly precipitation totals is much higher for the winter than for the summer half of the year for the other regions.

6.1.4 Resume

The regional precipitation characteristics, described within this section, strongly depend on the orographic structure of the study area. The mountainous regions in the south-west of the study area (TFM, WEG and EEG) are characterised by higher precipitation totals and percentile values, more frequent wet and rain days as well as a higher Simple Daily Precipitation Intensity index SDPI than those with lower average altitudes in the North-(east) (WSH, ESH, EML and LAS). Seasonal and monthly variations in the magnitude of individual indicators are in accordance with the annual precipitation cycle; with higher values in summer as compared to winter. Monthly precipitation data strongly depart from normal distribution, while the assumption of normal distribution, made for later trend analysis, is better met by the seasonal and annual precipitation totals. The departure of median from mean values is largest in March, July, September, October and December and lowest in February, June and November. For daily precipitation data the departure from normal distribution is even higher than for monthly data, reflected in very low values (zero or close to zero) for the percentiles below the median. A comparison of different percentile calculation approaches for daily precipitation totals was done. The percentile values of approach "pd" are considerably larger than those of method "ad". This could have a distinct influence on the trend results. On average the magnitude of 95P-ad and the 90P-pd is about 10 mm and the one of the 99P-ad about 20 mm, allowing some trend comparisons for the frequency of exceeding absolute (N-10mm and N-20mm) and relative (N-90P, N-95P and N99P) thresholds.

6.2 Drought and Wet Period Characteristics based on Monthly Indices

6.2.1 Percent of Normal Indicator PNI

The annual time series of the Percent of Normal Indicator PNI for 1900—2006 is displayed in Figure 6.3. Values above 100 percent indicate years with precipitation above the normal precipitation of the climate normal period 1961 to 1990 and analogously dry years are those with PNI values below 100%. Five years (1911, 1943, 1976, 1982 and 2003) are to be classified as extremely dry for the study area, as the mean PNI of all stations is below 75%. Extremely wet (> 125%) were more than twice as many years (eleven out of 107 years) namely 1905, 1915, 1926, 1930, 1941, 1954, 1965, 1974, 1981, 1995 and 2002. Due to the lower limitation of the PNI by value zero the driest events depart less strongly from normal precipitation than the wettest ones.

The Percent of Normal Indicator PNI has also been calculated and displayed for half years (Figure 6.4), seasons and single months (Annex 7). Most of the wet summer half years have been observed in the first half of the 20th century. For the winter half year a cluster of wet anomalies appeared at the end of the 20th century. Dry anomalies are distributed more equally over time than wet years for both half years. Great variations of the PNI magnitude appear from year to year in all time series of the PNI. Quite often, an extremely wet/ dry (half)year, season or month is followed by the other extreme, e.g., 1981 (wet) and 1982 (dry) as well as 2002 (wet) and 2003 (dry) in the annual time series. Furthermore, one half of the year might be extremely dry and the other one extremely wet. For instance the summer half year of 2003 has been extremely dry and the winter half year extremely wet.

When looking at the seasonal PNI time series, it becomes apparent that the PNI variability was particularly high in autumn (Annex 7). Correspondingly autumn showed the highest frequency of extremely dry (PNI < 50%, four cases) and extremely wet events (PNI > 150%, twelve cases). The extreme autumns are distributed quite evenly over time. For the summer season a cluster of wet years occurred at the beginning of the 20th century, as it has already been described for the summer half year. The same signal is basically visible in the monthly time series of June and July. The time series of the winter PNI stands out by a very pronounced oscillation between wet and dry extremes from the mid 1940s to the beginning of the 1950s. In the monthly PNI time series (December, January, February) this signal is not manifested that clearly, only in February a similar pattern can be seen.

Slightly more wet (54%) than dry (46%) years are measured by the PNI for the entire study period (Table 6.6). This is also true for extremely dry (PNI < 75%) and extremely wet (PNI > 125%) events. This bias of the annual PNI towards wet events may be due to the Normal Precipitation of 1961—1990 used for its calculation. On average, annual precipitation of 1961—1990 is more than 10 mm lower than the mean precipitation of the entire study period 1900—2006. Therefore, slightly more years are classified as "wetter than normal" compared to "drier than normal". On the other hand, most months show a bias to drier conditions. Besides differences in mean precipitation of the periods 1961—1990 and 1900—2006, this may be connected to the missing normal distribution of monthly precipitation totals, indicated by much smaller median values compared to the precipitation means for all months and periods (Table 6.6). Only July, with its very small mean precipitation values for 1961—1990 compared to 1900—2006, shows a bias to wet events like the one observed for annual data. The same is true for the summer season and the summer half of the year. For the other seasons PNI-values show a bias to more frequent dry events. Nevertheless, extremely wet events (> 150%) are considerably more frequent than extremely dry seasons (< 50%) for all seasons.

A characterisation of the PNI values including exceedance frequencies of selected upper and lower thresholds on a monthly, seasonal and annual basis is

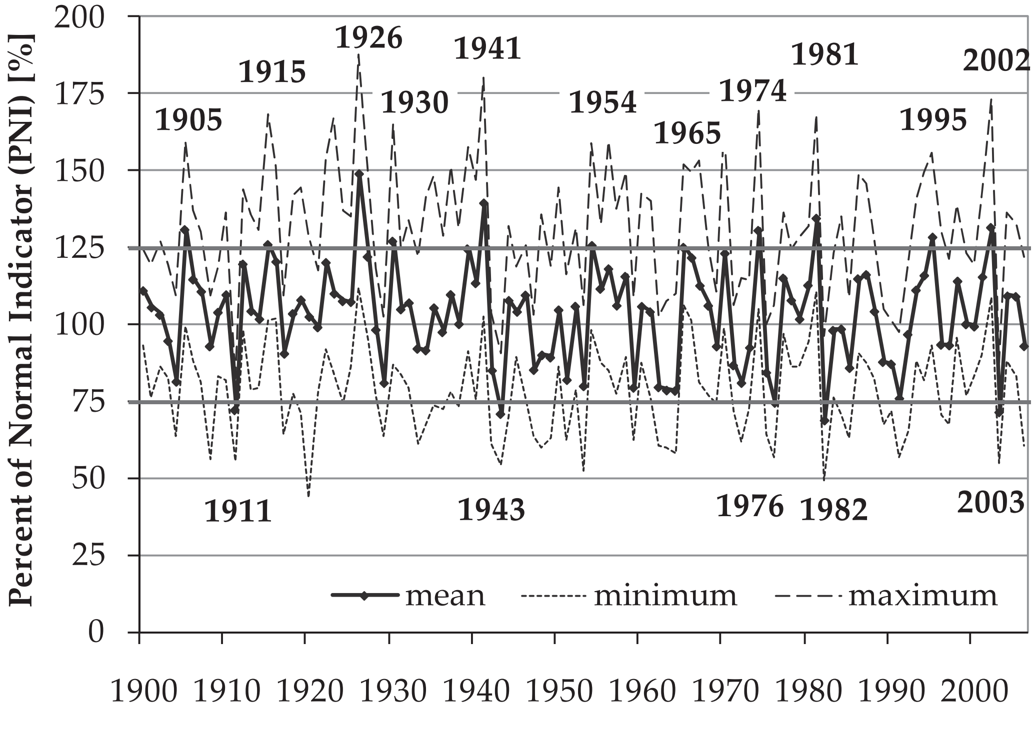


Figure 6.3: Annual Percent of Normal indicator (Mean, maximum and minimum PNI of 130 stations) with extremely dry (< 75%) and extremely wet years (> 125%) for 1900—2006

listed in Table 6.7. First it can be noticed that the larger the interval over which the data are averaged (from single months to complete years) the closer to 100% are the PNI values. For example, the highest values of mean PNI range from 215% in May to 391% in July and the lowest ones from 2% in October to

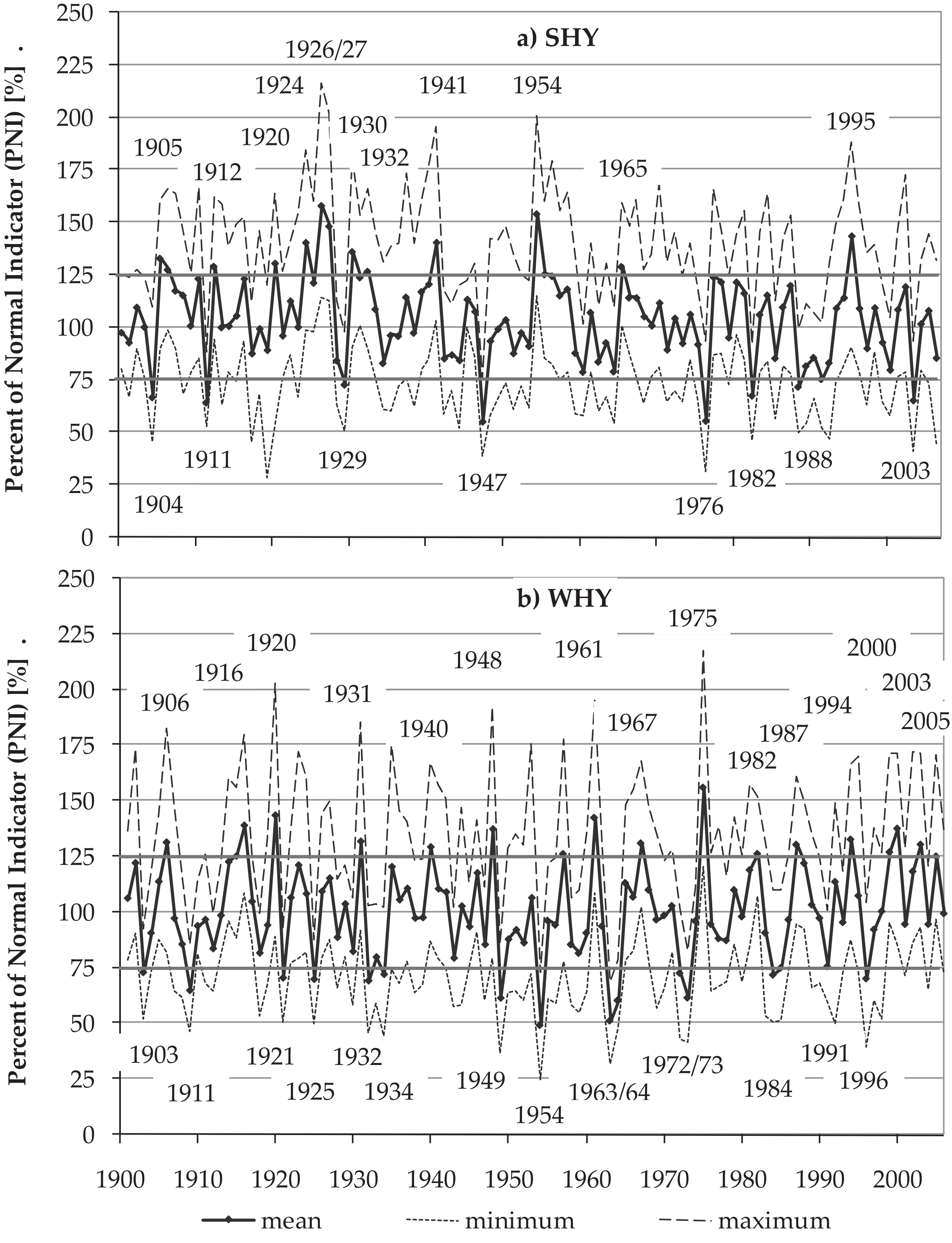


Figure 6.4: Percent of Normal indicator (Mean, maximum and minimum PNI of 130 stations) for a) the summer (SHY) and b) the winter half year (WHY) with extremely dry (< 75%) and extremely wet years (> 125%) for 1900—2006

31% in June. In contrast the annual values are 69% for the lowest and 149% for the highest mean PNI. Thus, the standard deviation of annual PNI is with about 11% much lower than the monthly one ranging between 21% in December and 40% in July. The highest departure from normal conditions was measured with 620 % in July 1954 at station Schlema-Wildbach. At several stations and in several months the precipitation total has been zero and therefore PNI-values of zero were calculated. Only for the months May, July and August the minimum station PNI-values are above zero.

Within the nine regions some differences in the annual PNI-characteristics can be noticed (Table 6.8). The highest regionally averaged annual PNI-values for 1951—2000 range between 129.5% in the 'Thuringian-Franconian Mountains' (TFM) and 139.4% in the regions 'Western Saxon Hilly Country' (WSH) and 'Lausitz and Spreewald' (LAS). The range of the lowest PNI averages is a little bit higher, ranging from 59.8% in region WSH to 72.0% in region WEG. Region

Table 6.6: Threshold characteristics of the PNI-indicator in comparison to the mean and median precipitation totals for 1961—1990 (normal precipitation) and 1900—2006 (entire study period); larger means, medians and percentages are marked by grey background colour)

	Percentage of stations with values below/above given thresholds						Average precipitation total		Median of precipitation total	
	< 50%	< 75%	< 100%	> 100%	> 125%	> 150%	1961 1990	1900 2006	1961 1990	1900 2006
Jan	14	34	56	44	28	17	49	50	41	45
Feb	17	34	53	47	31	18	43	44	41	41
Mar	17	38	57	43	29	19	47	49	43	42
Apr	19	42	62	38	22	12	57	52	55	48
May	15	36	59	41	23	12	66	64	61	59
Jun	13	35	56	44	25	13	77	75	74	71
Jul	13	26	42	58	42	29	68	84	64	76
Aug	15	36	58	42	25	15	76	75	69	68
Sep	17	36	56	44	28	18	54	55	51	50
Oct	22	38	53	47	34	24	47	51	37	44
Nov	18	37	56	44	27	16	53	52	51	49
Dec	20	42	62	38	24	14	60	56	52	50
Spr	2	22	59	41	15	5	170	165	165	159
Sum	2	15	46	54	25	9	221	235	217	228
Aut	5	22	52	48	23	12	154	158	151	151
Win	5	24	52	48	18	5	153	150	154	150
SHY	1	12	48	52	17	3	398	406	401	402
WHY	2	16	52	48	17	3	302	302	301	298
Ann	0	9	46	54	12	1	696	708	690	710

TFM shows the lowest percentage of values above the 125%-threshold (considerably wet years). Together with the low value of the highest measured PNI-average it can be assumed that this region is less affected by extremely

Table 6.7: Characteristic PNI values (Mean, Maximum, Minimum, standard deviation and percentage of stations beyond or below certain PNI-thresholds; all values in percent) for 1900—2006 (blue/ orange background colour: largest/ lowest values per month or season respectively)

	Mean		Minimum			Maximum			Std. dev.			< 75 %	< 50 %	< 25 %	> 175 %	> 150 %	> 125 %
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min						
Jan	278	6	54	195	0	176	428	17	25	61	3	33	12	2	10	19	30
Feb	350	14	52	150	0	177	543	35	26	97	6	33	15	3	11	19	31
Mar	277	18	51	195	0	171	460	32	25	67	5	40	17	3	12	19	29
Apr	231	30	48	159	0	159	350	56	24	57	9	42	18	2	6	11	22
May	215	20	45	119	4	179	357	46	29	64	9	35	15	3	7	13	24
Jun	288	31	49	180	5	187	463	75	29	67	13	36	14	2	7	14	26
Jul	391	22	62	260	0	245	620	66	40	94	10	24	11	3	22	32	45
Aug	246	23	47	141	2	190	489	53	31	88	10	33	15	3	9	17	28
Sep	264	4	48	165	0	189	508	36	29	93	7	37	17	4	11	18	28
Oct	337	2	59	240	0	187	540	8	27	112	3	35	21	8	17	26	38
Nov	244	10	52	160	0	164	371	19	24	55	4	39	19	4	10	19	29
Dec	252	8	49	135	0	149	427	18	21	53	4	42	21	5	6	12	21
Spr	167	53	62	120	24	142	239	75	17	33	9	23	3	0	1	5	16
Sum	217	42	69	144	19	164	320	75	20	36	10	14	3	0	4	12	29
Aut	196	38	68	143	7	152	284	66	18	47	8	22	5	0	5	12	25
Win	181	49	64	119	17	143	276	73	16	29	7	23	4	0	2	5	18
SHY	158	55	73	115	28	141	216	76	14	24	7	12	1	0	0	4	20
WHY	156	49	71	120	25	135	218	69	13	24	6	15	1	0	0	4	18
Ann	149	69	79	112	44	131	188	83	11	19	6	8	0	0	0	1	13

Table 6.8: Regional differences in the lowest (Min) and largest (Max) regional PNI-values for the annual PNI time series for 1951—2000 (blue/ orange background colour: region with the largest/ lowest mean PNI, respectively)

Annual data		TFM	VTB	WEG	OEG	EGF	WSH	ESH	EML	LAS	all stations
Mean	**Max**	129.5	134.4	137.6	138.1	134.5	139.4	138.7	135.8	139.4	134.5
PNI	**Min**	61.7	67.3	72.0	67.2	64.8	59.8	65.4	66.1	63.2	68.8
< 75%		9.0	8.4	4.7	8.2	10.3	10.4	8.9	9.5	8.2	8.5
< 50%		0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
< 25%		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
> 175%		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
> 150%		0.0	0.6	1.0	1.0	0.0	0.6	0.0	0.1	0.4	0.4
> 125%		9.2	11.1	10.3	11.3	11.1	13.6	11.2	12.9	12.6	11.5

wet years than other regions. Considerably wet and dry years seem to be particularly frequent in region WSH, showing the highest percentage of years with PNI > 125% and < 75 %, respectively. In contrast region WEG seems to be the region least affected by drought years; the percentage of years with PNI-values below 75% is just half the amount of other regions.

The Percent of Normal Indicator has been used to identify the driest and wettest years (Table 6.9), seasons and months (Annex 8) within the nine regions for period 1900—2006. Over the whole study area 1982, 1943 and 2003 have been the driest and 1926, 1941 and 1981 the wettest years. In most regions those years range under the ten driest and wettest years, respectively. As the time series of region TFM does not start until 1931, the wet year of 1926 cannot be represented in this region.

Table 6.9: Driest and wettest years measured by the PNI within the nine regions and for the entire study area for 1900—2006 (the three driest/wettest years for the entire study area are marked by orange/blue background colours)

		All stations	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS
Driest years	1	1982	1953	1964	1943	2003	1982	1982	1982	2003	1982
	2	1943	1964	1982	1982	1982	2003	1911	2003	1911	1943
	3	2003	1949	1948	1911	1943	1943	1991	1943	1976	2003
	4	1911	1959	1991	1959	1972	1951	1976	1976	1982	1976
	5	1976	1976	1911	2003	1904	1991	1964	1911	1943	1963
	6	1991	2003	1943	1985	1911	1911	1962	1991	1963	1972
	7	1964	1991	1962	1951	1962	1976	2003	1963	1991	1991
	8	1963	1933	1959	1964	1976	1964	1943	1972	1929	1929
	9	1959	1943	1947	1942	1959	1959	1904	1962	1904	1911
	10	1962	1942	1976	1929	1963	1962	1959	1964	1947	2006
Wettest years	1	1926	2002	1941	1926	1941	1926	1926	1926	1926	1926
	2	1941	1965	1981	1922	1926	1941	1941	1915	1941	1930
	3	1981	1981	1995	1941	2002	1981	1970	1916	1974	1981
	4	2002	1966	1926	1995	1922	2002	2002	1941	1905	1941
	5	1905	1986	1974	2002	1981	1954	1912	1930	1981	1974
	6	1974	1941	1970	1974	1905	1995	1905	1919	2002	1939
	7	1995	1970	1965	1954	1995	1905	1907	1923	1939	1905
	8	1930	1940	1905	1981	1954	1912	1956	2002	1994	1927
	9	1915	1995	2002	1965	1974	1939	1981	1981	1965	1956
	10	1954	1984	1954	1927	1915	1922	1927	1905	1956	1967

The driest summer half years have been 1911, 1947 and 1976 and the wettest ones 1926, 1927 and 1954 (Annex 8). In most months of the summer half year those years do not rank under the top three except 1911 and 1947 in August, 1926 in June, 1927 in April and 1954 in July. The summer season has almost the same top three like the summer half year, just the dry summer of 1947 is ranking on place four. The driest summer in all regions, except for VTB and TFM, where time series start in 1931 has been 1904.

For the winter half year the years 1954, 1963 and 1964 have been classified as the three driest and 1920, 1961and 1975 as the wettest ones (Annex 8). November 1953 and winter 1964 are the only matches for the top three of dry winter half years. October 1960 and 1974, December 1974 and November 1919 match the top three of wet winter half years. The wettest winter in most regions has been 1948 and the driest one 1964.

Regionally very homogeneous (at least seven out of nine regions with the same driest month, Annex 8) are the following driest months: January 1996 (9/ 9), February 1972 (8/ 9), May 1990 (8/ 9), September 1959 (8/ 9), November 1902 (8/ 8) and December 1972 (9/ 9). For the wettest cases, the same is true for January 1976 (9/ 9), February 1946 (8/ 9), June 1926 (8/ 8), July 1954 (8/ 9) and December 1974 (7/ 9).

6.2.2 Rainfall Anomaly Index RAI

Similar to the Percent of Normal Indicator PNI (6.2.1), the Rainfall Anomaly Index RAI can be used to characterise the dry and wet years, seasons and months. Additionally to the PNI the RAI includes the 10 most extremely dry and wet cases into the calculation. Negative RAI-values indicate precipitation conditions drier than normal and analogously positive RAI-values stand for conditions wetter than the average of 1961—1990.

On the basis of station-values, a RAI of less than -4/ more than +4 would correspond to extremely dry/ wet conditions. For the annual time series displayed in Figure 6.5, the RAI-thresholds for defining extremely dry/ wet years are reduced to –3/+3, as the RAI station values are averaged for the whole study area. Based on this definition, the years 1926, 1941, 1981 and 2002 have been extremely wet, and the years 1911, 1943, 1982 and 2003 extremely dry. Those have also been classified as extreme years using the PNI.

In comparison to the PNI, the regionally averaged RAI does not seem to have such a strong bias to either wet or dry events as described for the PNI. This is due to the simple normalisation procedure in the RAI calculation. Hence, the magnitude of the RAI values is not limited in one or the other direction, as the

PNI's magnitude has been. Nevertheless, the highest RAI values (max) depart more strongly from zero than the lowest ones (min). This is a relict of the skewness and lower limitation of the precipitation distribution.

Extremely wet over the whole study area have been the summer half years of 1926, 1954 and 1995, while the driest summers have been 1911, 1947, 1976, 1982 and 2003 (Figure 6.6). For the winter half year, all driest (1954, 1963, 1964 and 1973) and wettest events (1961 and 1975) have been observed in the second half of the 20th century.

A great year-to-year variability of the RAI can be noticed, like already described for the PNI. Extremely wet years may be followed by extremely dry ones as e.g., 1981 (extremely wet) and 1982 (extremely dry) in the annual RAI time series (Figure 6.5). The same is true for the years 2002 (wet) and 2003 (dry). However, there are also some periods of consecutive dry or wet years respectively. For instance, the summer half years from 1954 to 1958 all have been wetter than normal. An example for a sequence of dry summer half years is the period of 1988—1992. For the winter half year such long lasting sequences of dry or wet conditions, respectively, do not seem to be common.

The seasonal and monthly RAI time series are displayed in Annex 9. As already noticed for the winter PNI time series, the winter RAI shows a strong oscillation between dry and wet events from the mid 1940s to the beginning of

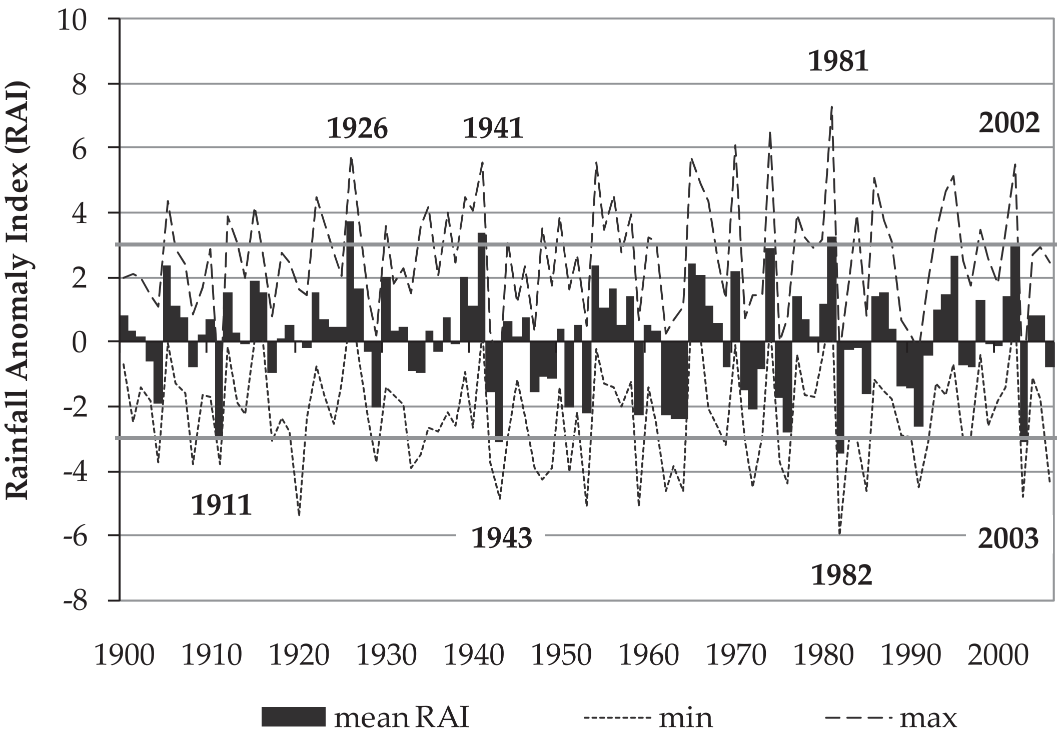


Figure 6.5: Annual Rainfall Anomaly Index RAI (Mean, maximum and minimum RAI of 130 stations) with extremely dry (RAI < -3) and extremely wet years (RAI > 3) for 1900—2006

the 1950's. The spring RAI time series is characterised by frequent dry year sequences, e.g. 1909—1913, 1945—1948, 1988—1993 and 1996—1999, whereas longer periods of consecutive wet springs very rarely occur. April stands out by an uninterrupted sequence of dry events from 1996 to 2006. The same is

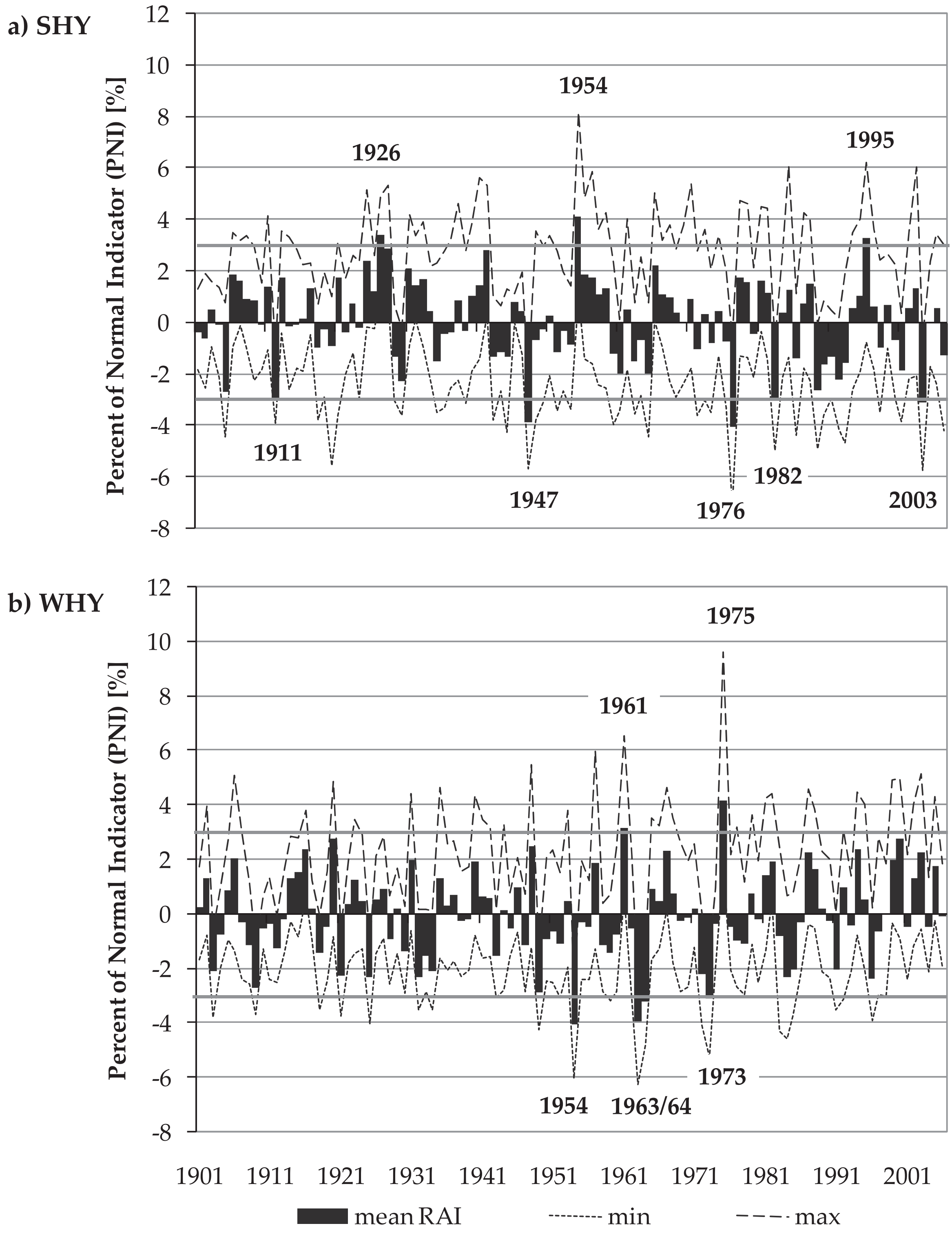


Figure 6.6: Rainfall Anomaly Index RAI (Mean, maximum and minimum RAI of 130 stations) for a) the summer (SHY) and b) the winter half year (WHY) with extremely dry (RAI < -3) and extremely wet years (RAI > 3) for 1900—2006

true for June as of 2000. July is characterised by frequent sequences of wet events whereas frequent dry event sequences have been observed in August, particularly since the 1950s. March and December show very long sequences of dry cases during the first part of the 20th century (March: 1908—1912 and 1927—1936; December: 1927—1938 and 1942—1947).

Due to the normalisation of precipitation in the RAI calculation procedure, mean RAI-values are close to zero (Table 6.10). The largest positive deviation of the regionally averaged monthly RAI (130 stations) from normal conditions has been observed with 6.0 in February and the largest negative deviation with -4.4 in January. The corresponding smallest deviations are 4.0 in May and -3.0 in June. Together with the maximum and minimum station RAI values ranging from 7.8 (November 2002 at station Greiz-Dölau) to 12.0 (December 1974, Gebelzig) and -5.4 (May 1990, Meuselwitz) to -4.5 (October 1943, Aue), respectively, the largest regional RAI deviations indicate a bias of the RAI

Table 6.10: Characteristic RAI values (Mean, Maximum, Minimum, standard deviation and percentage of stations beyond or below certain RAI-thresholds; all values in percent) for 1900—2006 (blue/ orange background colour: largest/ lowest values per month or season, respectively)

	Mean RAI			Minimum RAI			Maximum RAI			Std. dev.		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
Jan	-0.16	5.73	-4.41	-2.16	3.12	-5.31	2.16	11.13	-3.67	0.90	1.55	0.29
Feb	-0.14	6.00	-3.72	-2.07	1.92	-4.73	2.03	9.43	-2.78	0.87	1.97	0.32
Mar	-0.37	4.60	-3.59	-2.25	2.39	-4.55	1.70	9.23	-2.76	0.84	1.57	0.25
Apr	-0.45	4.72	-3.19	-2.30	2.38	-4.99	2.17	9.97	-2.00	0.97	2.00	0.40
May	-0.30	3.97	-3.77	-2.49	0.89	-5.41	2.90	8.43	-2.49	1.12	2.19	0.41
Jun	-0.28	5.56	-3.02	-2.51	2.97	-4.67	3.04	8.82	-1.06	1.16	2.07	0.66
Jul	0.12	5.68	-3.69	-1.96	2.84	-5.14	2.50	10.11	-1.61	0.95	1.69	0.44
Aug	-0.21	4.59	-3.58	-2.42	1.73	-4.98	2.80	10.29	-2.20	1.12	2.44	0.39
Sep	-0.26	4.85	-4.15	-2.20	1.65	-5.10	2.38	7.96	-2.56	0.97	1.87	0.37
Oct	-0.16	4.93	-3.58	-1.70	2.73	-4.51	1.57	9.47	-3.19	0.69	1.78	0.16
Nov	-0.27	4.81	-3.77	-2.16	1.82	-4.57	2.03	7.84	-3.44	0.88	1.72	0.21
Dec	-0.49	5.39	-4.01	-2.14	1.37	-5.09	1.52	12.02	-3.21	0.77	1.85	0.22
Spring	-0.29	4.15	-3.51	-2.62	1.37	-5.83	2.59	8.79	-1.70	1.10	1.86	0.53
Summer	0.13	4.63	-4.20	-2.46	2.09	-6.34	2.84	8.29	-2.22	1.12	1.79	0.55
Autumn	-0.08	4.16	-3.78	-2.04	2.13	-6.16	2.09	7.32	-2.19	0.87	1.67	0.52
Winter	-0.13	4.98	-3.33	-2.28	1.14	-5.26	2.43	8.96	-1.93	0.97	1.82	0.46
SHY	0.10	4.11	-4.06	-2.34	1.10	-7.06	2.77	8.21	-2.12	1.07	1.66	0.41
WHY	-0.04	4.20	-4.06	-2.12	1.68	-6.23	2.24	9.65	-2.65	0.92	1.50	0.51
Annual	0.14	3.75	-3.49	-2.25	1.15	-5.99	2.59	7.28	-1.90	1.01	1.48	0.55

towards higher positive extremes (wet events). Due to the longer timeframes, over which the precipitation is averaged, the seasonal and annual maximum and minimum RAI deviations from normal conditions are generally smaller than the monthly ones. The standard deviation of monthly as well as seasonal and annual RAI values is about 1 and may vary from 0.16 to 2.44.

The characteristic allocation of monthly, seasonal and annual RAI-values in one of the nine RAI classes (please refer to Table 2.2) is given in Table 6.11. Normal conditions with RAI-values ranging from -1 to +1 occur in 34% (December) to 43% (July and autumn) of the cases. For most months the RAI shows a bias towards slightly (-2.00 ≤ RAI ≤ -1.01) to considerably dry events (-4.00 ≤ RAI ≤ -3.01), whereas extremely dry conditions (RAI < -4.00) occur less often than extremely wet (RAI > 4.00) conditions. This is illustrated by the example of August (Figure 6.7b). Only July is showing a higher frequency in the class of slightly wet events in comparison to slightly dry events (Figure 6.7a, Table 6.11). The most uniform frequency distribution of RAI classes has been observed for the half years (SHY: Figure 6.7c).

Table 6.11: Percentage of stations within the given RAI classes for 1900—2006

	RAI > 4.00	3.01 – 4.00	2.01 – 3.00	1.01 – 2.00	-1.00 – 1.00	-2.00 – -1.01	-3.00 – -2.01	-4.00 – -3.01	RAI < -4.00
Jan	2.6	3.1	6.4	12.8	37.7	18.3	13.0	4.1	1.8
Feb	2.4	3.6	7.3	13.3	38.6	15.7	11.8	6.8	0.5
Mar	2.7	3.3	6.8	11.1	35.0	18.7	15.7	6.2	0.5
Apr	2.9	3.3	5.7	10.0	33.6	19.3	18.7	6.2	0.3
May	2.8	3.2	6.0	10.7	37.8	19.9	12.7	6.0	0.9
Jun	2.6	3.3	6.8	12.2	35.3	17.5	15.5	6.0	0.7
Jul	2.6	2.9	7.3	15.9	42.6	11.9	9.6	6.2	0.9
Aug	3.0	2.9	5.9	11.2	37.3	18.9	14.2	6.1	0.7
Sep	2.5	3.5	6.8	11.5	37.9	18.0	13.7	4.7	1.4
Oct	3.0	2.5	6.1	13.2	37.7	15.7	14.7	7.0	0.1
Nov	2.6	3.6	7.1	11.6	36.2	17.2	15.1	6.4	0.3
Dec	2.7	3.0	6.7	10.0	34.0	20.6	16.5	5.5	0.9
Spr	2.9	3.2	6.1	11.0	37.1	19.7	13.5	5.5	0.9
Sum	2.5	3.4	8.1	16.0	41.1	13.7	8.6	4.5	2.1
Aut	2.6	3.9	6.7	11.5	43.2	15.3	10.0	5.6	1.2
Win	2.7	3.1	7.3	14.4	39.2	14.0	11.9	6.6	0.8
SHY	2.2	3.8	9.1	15.3	39.1	14.5	9.6	4.5	1.9
WHY	2.1	4.4	8.7	12.9	40.9	15.0	9.0	5.0	2.0
Ann	1.9	4.6	10.1	16.5	36.2	13.2	10.7	5.3	1.5

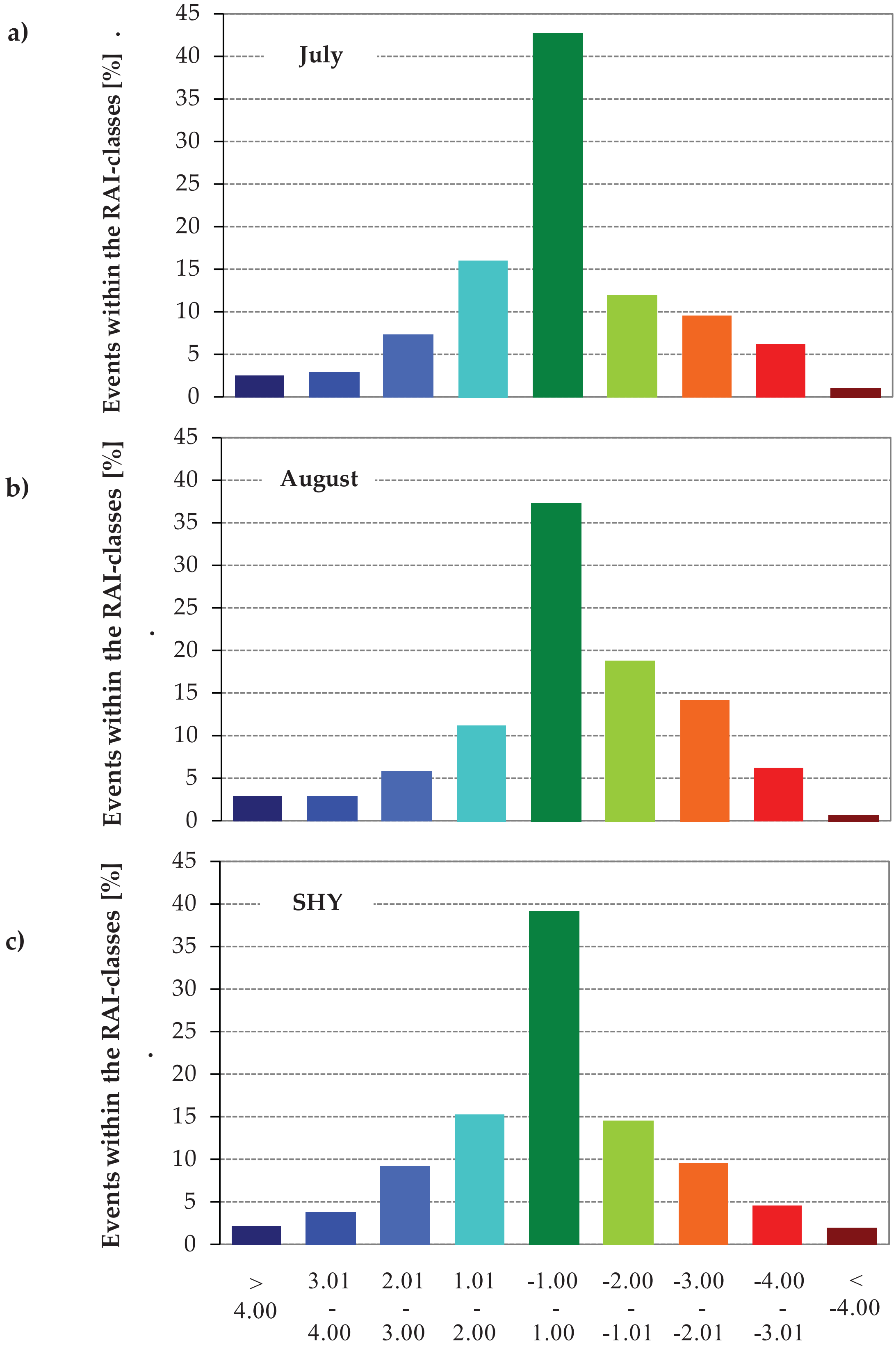


Figure 6.7: Frequency distribution of the nine RAI classes for a) July, b) August and c) the summer half year for 1900—2006

Regional differences in the RAI characteristics including the exceedance probabilities of several RAI-thresholds are illustrated for annual values in Table 6.12.

Most regions show a bias to dry conditions (RAI < -2). Only in the regions TFM (Thuringian-Franconian Mountains), WSH (Western Saxon Hilly Country) and LAS (Lausitz and Spreewald) the frequency of wet and dry years is almost equal. Region TFM is the only region with a higher frequency of considerably wet events (RAI > 3) than considerably dry events (RAI < -3). However, extremely wet years are more frequent than extremely dry ones in all regions, except for EGF (Erzgebirge Foreland), WSH and LAS. In region EGF notably less frequent wet years occur in all classes (lowest values of all regions) matching the lowest value in the maximum regional RAI-average.

Like the PNI the RAI has been used to identify the driest and wettest years (Table 6.13), seasons and months (Annex 10) within the nine regions for period 1900—2006. The three driest years over the whole study area have been 1982, 2003 and 1943 and the wettest ones 1926, 1941 and 1981, matching the PNI results. Those years belong to the top 10 of dry and wet years in all sub-regions except 1982 for region TFM and 2003 for region VTB. Both regions are situated in the southwest of the study area and particularly region TFM quite often shows considerably different precipitation characteristics than the rest of the study area. 1926 can not rank under the ten wettest years in region TFM as its time series only starts as of 1931.

On the basis of half years 1947, 1976, 2003 have been the driest, and 1926, 1954, 1995 the wettest summers, while the winters were driest in 1954, 1963, 1964, and wettest in 1920, 1961, 1975 (Annex 10). The three driest/ wettest seasons have been:

Spring:	1941, 1976, 1990	/	1941, 1961, 1965
Summer:	1904, 1911, 1976	/	1926, 1954, 1955
Autumn:	1948, 1953, 1982	/	1952, 1974, 1998
Winter:	1964, 1973, 1996	/	1916, 1948, 1987

For half years, seasons and months, the differences in the ranking of dry and wet years between the indicators RAI and PNI are larger than for the annual precipitation time series (Annex 8 and Annex 10). Nevertheless, some particularly dry/ wet months with a high regional similarity (at least seven out of nine regions with the same driest/ wettest months) are identically identified. Those were the dry months of January 1996 (9/ 9 regions), February 1972 (7/ 9), May 1990 (9/ 9), September 1959 (8/ 9), and December 1972 (9/ 9). For the wettest cases the same is true for January 1976 (9/ 9), February 1946 (8/ 9), June 1926 (7/ 8), July 1954 (8/ 9) and December 1974 (7/ 9). Additionally the RAI identified September 1952 (7/ 9) and November 2002 (7/ 9) as wettest in the majority of regions (Annex 10).

Table 6.12: Regional differences in the lowest (Min) and largest (Max) regional RAI-values for the annual RAI time series for 1951—2000 (blue/ orange: region with the largest/ lowest mean RAI, respectively)

Annual data		TFM	VTB	WEG	OEG	EGF	WSH	ESH	EML	LAS	all stations
Mean	**Max**	3.41	3.50	3.68	3.29	2.99	3.51	3.49	3.36	3.60	3.27
RAI	**Min**	-3.98	-3.73	-3.64	-3.61	-3.82	-4.16	-4.01	-3.58	-4.06	-3.49
< -2		17.7	18.1	19.3	18.0	18.3	17.4	19.2	17.4	16.5	17.9
< -3		5.3	7.8	6.7	5.5	7.2	7.4	7.3	7.5	6.4	6.7
< -4		1.6	2.3	1.3	1.0	0.7	2.0	1.2	0.5	1.4	1.4
> 4		1.9	2.4	2.3	1.3	0.7	0.9	1.6	1.1	1.1	1.5
> 3		8.0	6.8	6.6	4.8	3.0	5.3	5.3	4.8	5.1	5.7
> 2		17.2	16.6	14.7	12.8	11.8	17.2	16.6	16.1	16.4	15.8

Table 6.13: Driest and wettest years measured by the Rainfall Anomaly Index RAI within the nine regions and for the whole study area for 1900—2006 (the three driest/ wettest years over the entire study area are marked by background colours)

		All stations	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS
Driest years	**1**	1982	1953	1964	1982	2003	1982	1982	1982	2003	1982
	2	2003	1964	1982	1959	1982	1943	1991	2003	1976	1943
	3	1943	1949	1991	1943	1943	2003	1911	1976	1982	2003
	4	1911	1976	1948	1911	1972	1991	1976	1943	1911	1976
	5	1976	2003	1911	2003	1904	1951	1964	1911	1963	1963
	6	1991	1959	1962	1985	1911	1911	1962	1991	1991	1972
	7	1964	1933	1943	1951	1962	1976	2003	1963	1943	1991
	8	1963	1991	1959	1964	1976	1964	1943	1972	1929	1929
	9	1959	1943	1976	1963	1959	1959	1904	1962	1904	1911
	10	1962	1942	1947	1942	1963	1962	1959	1964	1964	2006
Wettest years	**1**	1926	1965	1981	1926	1941	1926	1926	1926	1926	1926
	2	1941	1981	1995	1922	2002	1941	1941	1941	1974	1981
	3	1981	2002	1974	1995	1981	1981	1970	1915	1941	1941
	4	2002	1966	1941	2002	1926	1954	2002	1981	1981	1930
	5	1974	1970	1970	1974	1995	2002	1912	2002	2002	1974
	6	1995	1986	1965	1941	1954	1995	1956	1930	1994	1939
	7	1965	1941	1926	1954	1974	1974	1974	1974	1965	1956
	8	1954	1940	1905	1981	1922	1905	1905	1995	1905	1967
	9	1905	1995	2002	1965	1905	1912	1981	1954	1956	2002
	10	1970	1984	1954	1970	1939	1922	1907	1916	1954	1993

Figure 6.8 illustrates exemplary the spatial distribution of RAI values for one extremely dry (May 1990) and one extremely wet month (January 1976) as well as for one month with a high regional differentiation in magnitude and sign of RAI values (November 1968).

The extreme conditions might be quite homogenous over the whole study area like for May 1990 and January 1976. Large gradients over a comparatively short distance are possible, too, as the example of November 1968 shows. During this month considerably and extremely wet conditions were observed in the North (EML) and East (LAS) of the study area, while the 'Thuringian-Franconian Mountains' (TFM) were characterised by precipitation totals below

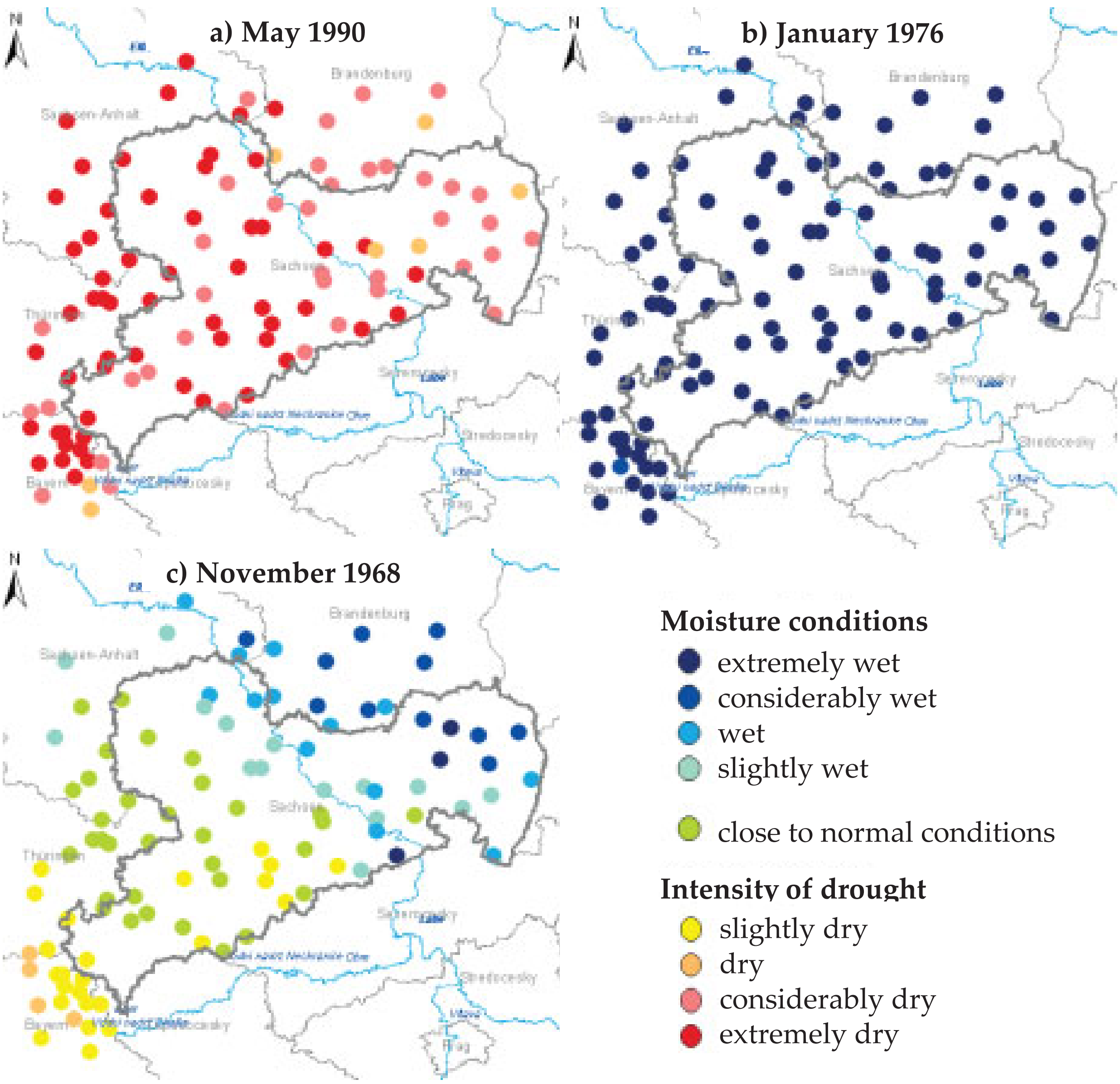


Figure 6.8: Maps of the monthly RAI values for a) an extremely dry month (May 1990), b) an extremely wet month (January 1976) and c) a month with a high regional differentiation in the RAI values (November 1968)

normal conditions. Gradients quite often occur from the mountains in the South-(West) to the lowlands in the North-(East), but also from West to East following the prevailing wind directions in the westerlies.

6.2.3 Decile Dry and Wet Periods

The decile indicator is used to describe long term drought and wet period conditions lasting at least three months. Decile dry and wet periods differ from each other by their characteristic durations (Figure 6.9; Table 6.14, Table 6.15). Decile dry periods generally last much longer than wet periods. For the shortest durations (up to the 10th percentile), the distributions of decile wet and dry periods are quite similar. About ten percent of all dry and wet periods last about four to five months. While 50 percent of all decile wet periods last three to six months, the median of decile drought duration is approximately eight months. For the 90th percentile the differences between decile dry and wet period durations are even higher. Less than ten percent of the decile wet periods last longer than ten months, whereas the same is true for decile droughts lasting longer than 19 months.
An average decile drought occurs about 4.5 times in 10 years and lasts approximately 10 months (Table 6.14). In contrast, an average decile wet period occurs with about five times in 10 years slightly more frequent than a decile

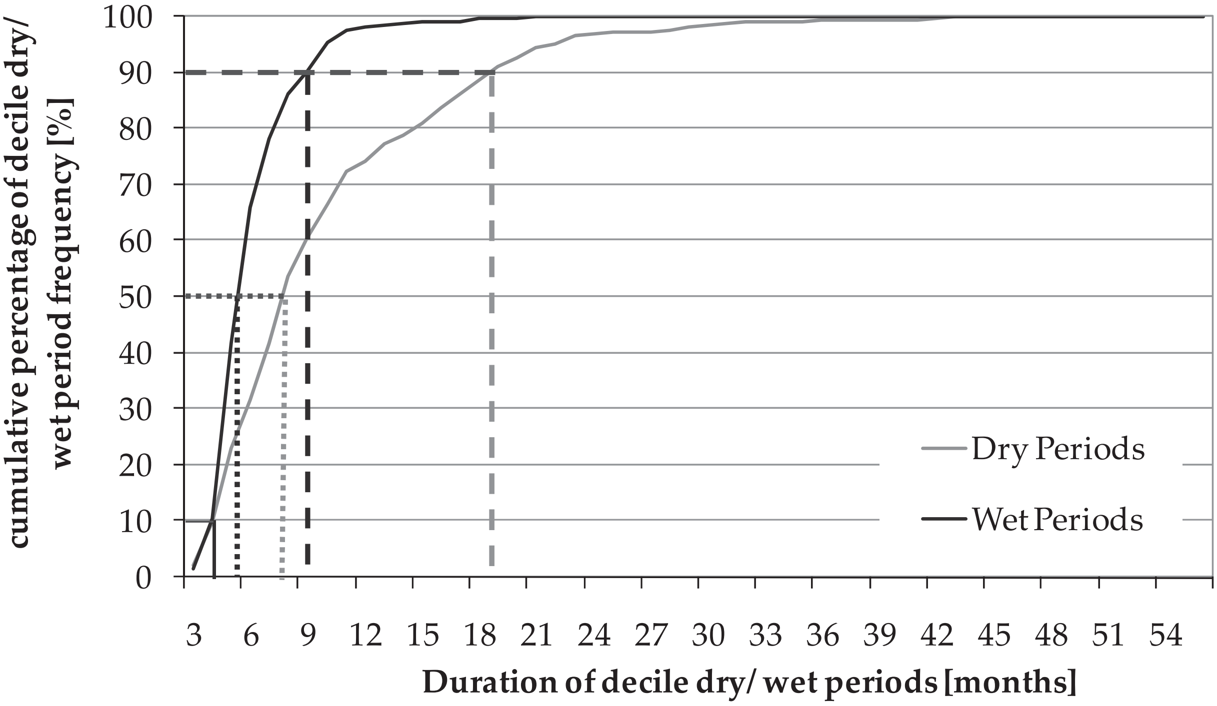


Figure 6.9: Cumulative frequency distribution of decile dry and wet period durations for the whole study area (130 stations); 1900—2006

drought, while the duration of decile wet periods is with an average of 6.5 months considerably shorter than the one of decile droughts (Table 6.15). The longest decile dry period lasted 54 months from January 1989 to June 1993 and has been observed at the stations Johnsdorf-Kurort/ LAS and Skassa/ ESH. Matching the shorter mean duration of wet periods in comparison to dry periods, the longest decile wet period lasted 31 months (November 1965 to May 1968) and has been observed at station Selb/ TFM.

The nine regions differ just slightly in the average decile characteristics as the decile indicator is calculated relative to the absolute station values (Table 6.14, Table 6.15). At single stations the frequency of decile droughts varies between 3.4 (EGF) to 5.5 (VTB) events per 10 years and the one of wet periods between 4.2 (TFM) to 5.9 (WEG, LAS). Dry periods have an average duration of 8.1 months (EML) to 13.0 months (EGF), while the wet period duration ranges from 5.5 months (LAS) to 7.6 months (TFM). Considerable differences between the decile wet and dry periods were also observed for the standard deviation of the duration of such period. The standard deviation of wet period duration ranges from 1.3 months (WSH) to 5.2 months (TFM), whereas the standard deviation of dry periods is on average about 3 times as high as the one of wet periods ranging from 3.8 months (VTB, LAS) to 10.9 (EEG) months.

The regional average of the maximum dry period duration observed in period 1900—2006 is between 24.6 months in the Western Saxon Hilly Country (WSH) and 35.3 months in the Eastern Erzgebirge (EEG, Table 6.14). On the basis of station values, the maximum drought duration ranges from 17 months (LAS)

Table 6.14: Statistic characterisation of decile dry period frequency and duration within the nine regions (130 stations) for 1900—2006

	Decile dry period frequency per 10 a			**Decile dry period duration**								
				Mean			**Std. dev.**			**Maximum**		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
TFM	4.5	5.1	4.1	10.2	11.2	8.9	6.2	7.9	4.5	28.0	42	20
VTB	4.7	5.5	3.9	9.9	12.0	8.8	5.5	9.5	3.8	24.5	43	19
WEG	4.6	5.0	4.2	10.2	11.5	8.5	6.1	7.9	4.1	28.2	42	21
EEG	4.3	5.0	3.6	11.2	12.7	9.6	7.4	10.9	5.7	35.3	46	24
EGF	4.2	4.7	3.4	10.5	13.0	9.9	6.2	8.2	4.8	32.2	43	22
WSH	4.6	5.4	3.9	9.8	11.2	8.6	5.6	7.9	3.9	24.6	42	19
ESH	4.2	5.1	3.6	10.5	12.3	8.4	6.8	10.4	4.3	31.2	54	20
EML	4.6	5.4	3.8	9.6	11.0	8.1	5.8	7.3	4.1	28.3	43	21
LAS	4.4	5.1	3.8	10.0	11.7	8.5	6.1	9.4	3.8	30.6	54	17
Total	4.5	5.5	3.4	10.2	13.0	8.1	6.2	10.9	3.8	28.9	54	17

to 54 months (ESH, LAS). For wet periods (Table 6.15), the maximum duration is with 14 months on average approximately half as long as the one of droughts. Regionally, it differs from 11.4 months (VTB) to 16.0 months (TFM, EML). The lowest station maximum is 9 months (VTB, WSH) and the highest one 31 months (TFM).

Printing the occurrence of decile droughts (Figure 6.10) and wet periods (Figure 6.11) at all stations into one graph delivers some spatial drought and wet period patterns. Decile dry and wet periods frequently occur at a very high percentage of stations at the same time, indicating that the occurrence of drought and wet periods is triggered by some larger scale atmospheric processes. Furthermore, the chosen regional classification is confirmed, as some dry/ wet periods occur with a very high spatial coverage in selected regions, whereas in other regions no decile drought or wet period respectively is observed at the same time.

Periods of clustered supra-regional decile dry period occurrence lasting four to 13 years alternate with periods of less frequent, shorter and/ or spatially less extended dry periods, generally lasting two to five years (Figure 6.10). The periods 1942—54, 1958—64, 1969—78, 1982—86 and 1989—93 are examples of such drought year clusters. The same phenomenon of clustered decile periods may be observed for wet events (Figure 6.11). Some periods like 1953—58 characterised by a pronounced clustering of wet periods alternate with periods where wet events occur very rarely, e. g., 1962—64 or 1988—92.

Table 6.15: Statistic characterisation of decile wet period frequency and duration within the nine regions (130 stations) for 1900—2006

	Decile wet period frequency per 10 a			Decile wet period duration								
				Mean			Std. dev.			Maximum		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
TFM	5.0	5.6	4.2	6.6	7.6	6.0	2.7	5.2	1.9	16.0	31	11
VTB	5.1	5.8	4.6	6.4	6.8	5.7	1.8	2.9	1.5	11.4	19	9
WEG	5.1	5.9	4.3	6.3	7.2	5.8	2.1	3.1	1.4	12.9	23	10
EEG	5.0	5.6	4.6	6.4	7.1	5.8	2.1	3.2	1.5	12.4	21	10
EGF	5.1	5.3	4.8	6.5	6.8	6.2	2.1	2.9	1.6	13.5	20	10
WSH	5.1	5.7	4.5	6.5	6.9	6.0	2.0	3.1	1.3	13.1	20	9
ESH	4.9	5.4	4.3	6.6	7.1	6.1	2.3	3.4	1.5	13.7	19	10
EML	4.9	5.4	4.3	6.6	7.2	5.9	2.4	3.4	1.6	16.0	25	10
LAS	4.9	5.9	4.5	6.6	7.4	5.5	2.5	4.6	1.6	15.3	24	10
Total	5.0	5.9	4.2	6.5	7.6	5.5	2.3	5.2	1.3	14.0	31	9

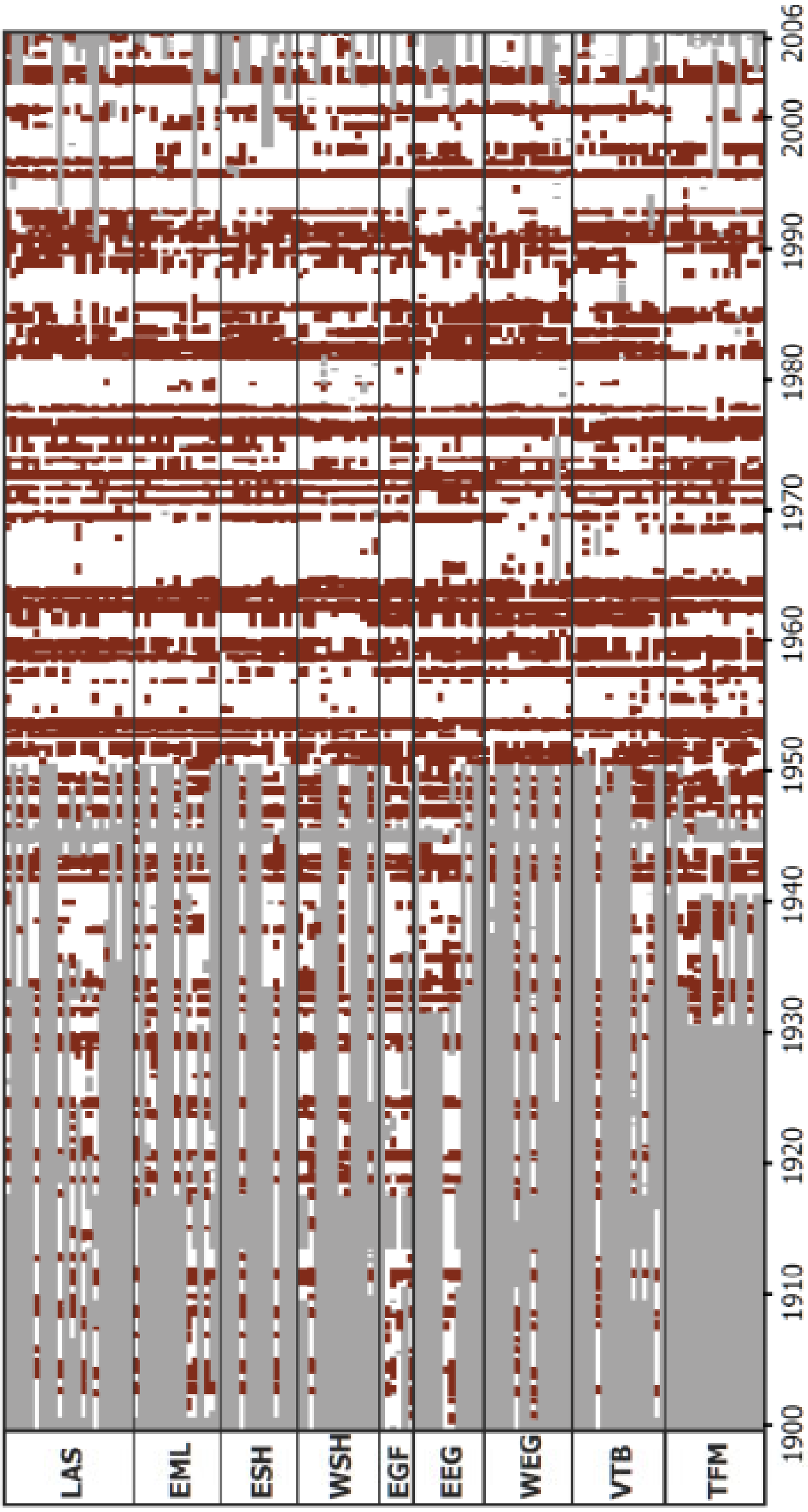


Figure 6.10: Timing of decile droughts (orange bars) at 130 stations within the nine regions for 1900—2006 (missing data are indicated by grey bars)

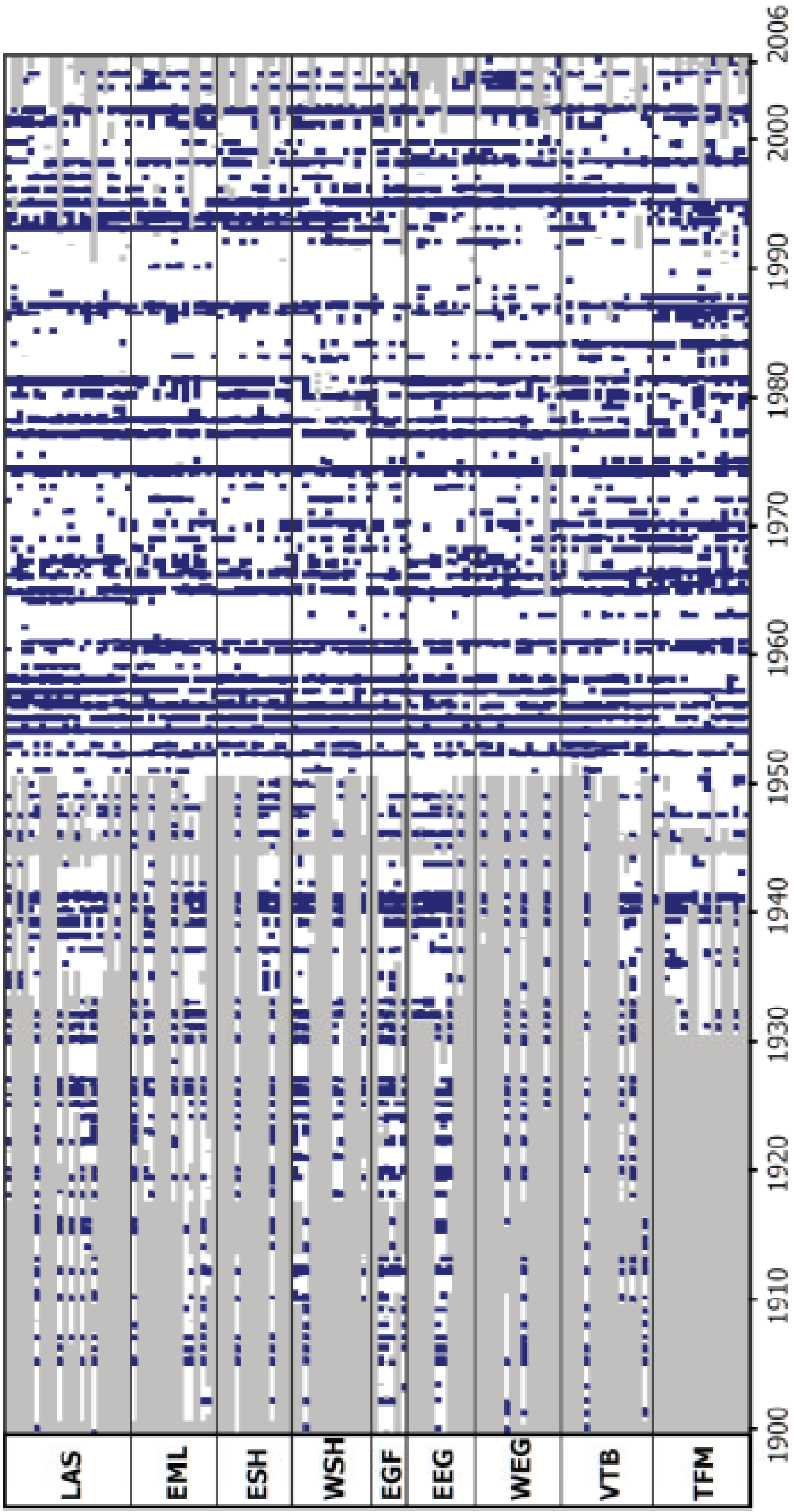


Figure 6.11: Timing of decile wet periods (blue bars) at 130 stations within the nine regions for 1900—2006 (missing data are indicated by grey bars)

At the beginning of the study period (until the 1940s) and in recent times (since the mid 1990s) the clustering of decile dry periods is less pronounced over the whole study area than in the intermediate period (Figure 6.10). For decile wet periods a less pronounced clustering of periods with high spatial wet event coverage has been observed from the 1960s to the beginning of the 1990s (Figure 6.11).

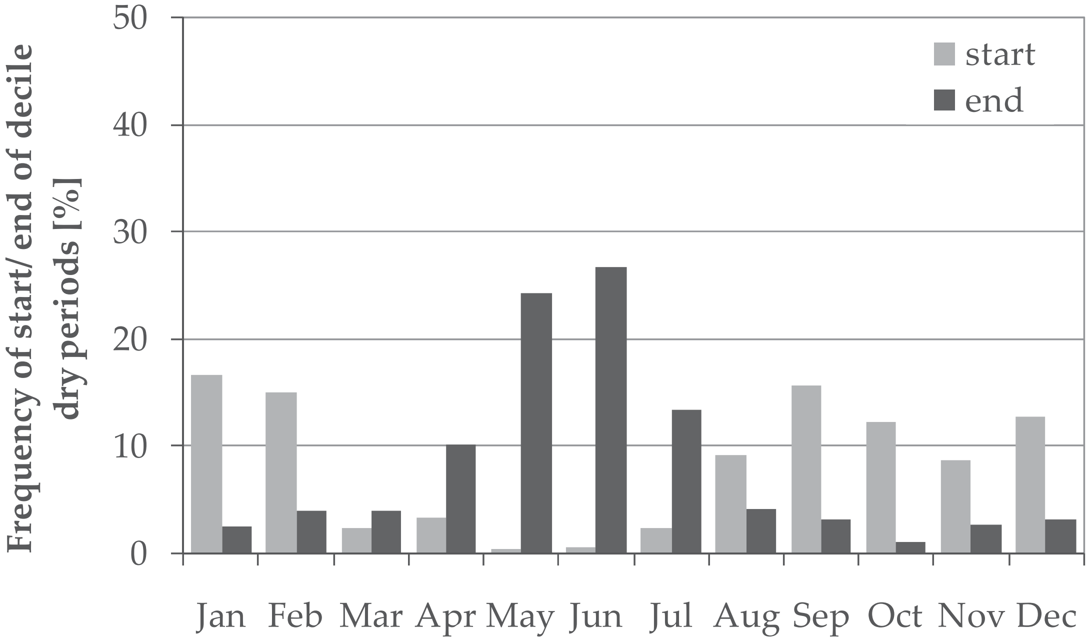


Figure 6.12: Timing (month of start/ end) of decile droughts observed at 130 stations for 1900—2006

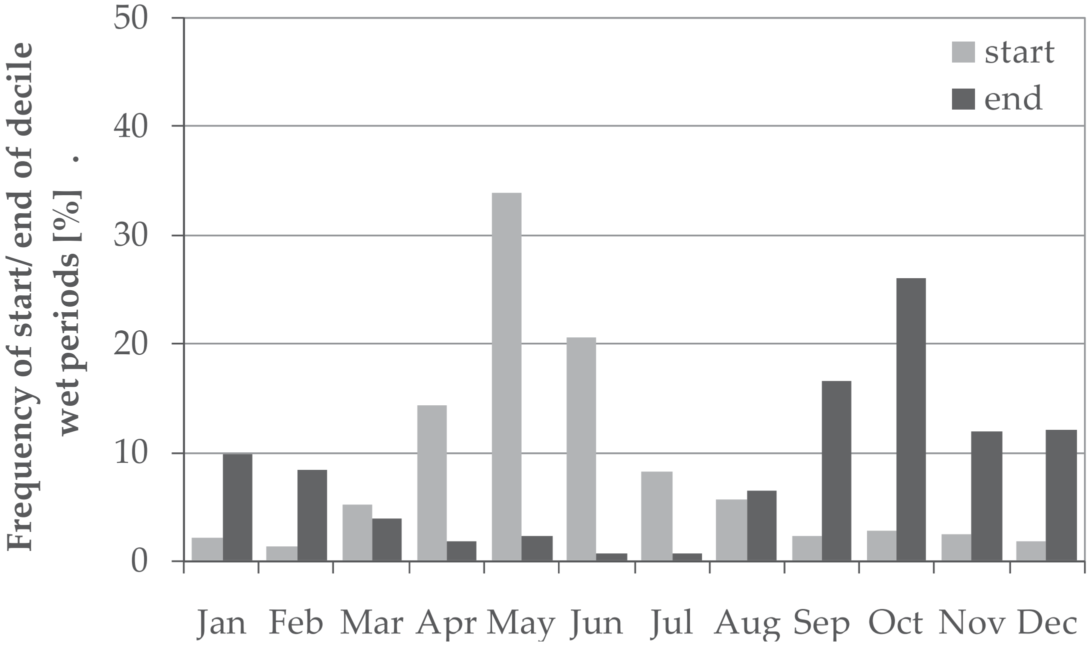


Figure 6.13: Timing (month of start/ end) of decile wet periods observed at 130 stations for 1900—2006

The characteristic months in which decile dry (Figure 6.12) and wet (Figure 6.13) periods start and end depend on the annual precipitation cycle, as the decile thresholds are defined on the basis of a general distribution of 3-month totals. Seasonal differences in the magnitude of the 3-month precipitation totals might be incorporated in the decile index by calculating the distribution and connected decile thresholds separately for every of the twelve cases.

The month in which a dry/ wet period starts is defined as the first months of the 3-month precipitation total falling under the first decile (10^{th} percentile) of the distribution of 3-month-precipitation totals. Correspondingly, the last month of the last 3-month total within the dry/ wet period is defined to be the end of the drought or wet period, respectively. According to those definitions, decile droughts frequently start in autumn and winter and end in spring and summer (Figure 6.12). The opposite is true for decile wet periods that most often start in May and end in October (Figure 6.13).

6.2.4 Resume

The indicators PNI and RAI quite similarly identified the driest and wettest years, seasons and months within the study area. The years 1904, 1911, 1929, 1942/43, 1951, 1953, 1959, 1962 to 1964, 1972, 1976, 1982, 1991, 1996 and 2003 have been particularly dry within most regions, while 1905, 1915, 1926/27, 1930, 1939, 1941, 1954, 1965/66, 1970, 1974, 1981, 1995 and 2002 have been severely wet. Quite often an extremely wet or dry year was followed by the other extreme, but there were also dry or wet departures from normal conditions that continued for several months, seasons or years with variable severity. The large positive RAI and PNI anomalies in January 1976, February 1946, June 1926, July 1954 and December 1974 have been regionally most homogenous, while the highest negative anomalies occurred in January 1996, February 1972, May 1990, September 1959 and December 1972.

The indicators RAI and PNI were slightly biased towards wet extremes for annual data, while dry events were more frequently identified for most months and seasons than wet events. This may be due to changes in precipitation totals during the study period and the deviation of precipitation data from normal distribution. Nevertheless, extremely wet conditions (PNI > 150%, RAI > 4) occurred more frequently than extremely dry conditions (PNI < 50%, RAI < -4) in most months and seasons. This is probably due to the fact that precipitation is limited below.

Years identified as particularly dry or wet by the RAI and PNI indicator, were quite often affected by decile dry or wet periods, respectively. An average decile drought lasted for about 10 months and occurred 4.5 times within 10 years, while decile wet periods occurred with 5 times in 10 years slightly more frequent, but lasted on average only 6.5 months. The regional differences in decile dry and wet period characteristics were very small. Decile dry and wet periods often occured at a high percentage of stations at the same time with similar durations, whereby the spatial extent of decile droughts was generally higher than for wet periods. This indicates, that the occurrence of decile dry periods was predominantly triggered by some larger scale atmospheric processes and that regional small-scale precipitation characteristics had more influence on decile wet periods. Furthermore, several decile dry or wet periods frequently occured clustered in time. Periods of clustered drought occurrence are 1942—1953, 1958—1964, 1970—1978, 1982—1986 and 1989—1993. Similar pattern have been noticed for decile wet periods that occurred particularly frequent between 1953 and 1958, showing a high spatial coverage in addition. In other periods of clustered wet period occurrence like 1965—1970 or 1993—1999 the spatial coverage of single wet periods was less pronounced.

Following the annual precipitation cycle, decile dry periods started most often in the months with lower precipitation totals (autumn and winter) and were terminated in summer. Analogously, decile wet periods often started in April to June and ended in September to December.

6.3 Extreme Precipitation Description based on Daily Indices

6.3.1 Heavy Precipitation Indicators

A variety of different indicators is used to describe the heavy precipitation characteristics of Saxon climate. Annual averages for the nine regions are displayed in Table 6.16, monthly and seasonal values may be found in Annex 11. The thresholds of 10 and 20 mm (N-10mm, N-20mm), respectively, are exceeded 17.5 and 4.2 times per year. The magnitude of the highest precipitation event (Mx-R) per year averages about 40 mm. Based on those absolute thresholds, heavy precipitation events occur most frequently in the mountainous regions (WEG, EEG), whereas they are particularly rare at lower altitudes (EML, WSH), matching the spatial gradient of precipitation totals. For the relative percentile thresholds the regional differences are much smaller, but there is still a gradient from the northern lowlands (WSH, EML) to the southern mountainous areas (WEG, EEG).

For calculating the percentiles, two methods abbreviated with ‘ad’ and ‘pd’ are discussed in the literature (section 2.3) and used within this study. When all days are included into the percentile calculation (method ‘ad’) the 90th percentile of 5.9 mm (Mgt-90P) is exceeded about 34 times (N-90P), the 95th percentile

(Mgt-95P: 9.5 mm) 17 times (N-95P), and the 99th percentile (Mgt-99P: 20.0 mm) 3.6 times (N-99P) per year (Table 6.16). As the magnitude of the percentiles is higher when only days with precipitation above zero (method 'pd') are considered, the exceedance frequency of those 90th, 95th and 99th percentiles is lower than for the 'ad'-method. The average precipitation intensity on days above the 95th percentile (API-95P) is 17.6 mm for the 'ad'-method and 23.0 mm for the 'pd'-method. About 41.9% of total precipitation is falling in days above the 95th percentile (PP-95P), when using the 'ad'-method, while the percentage for the 'pd' method is only 27.6%. The already described regional differences emerge also in the results of the 'API'-indicators, but not in the regional averages of the 'PP'-indicators. Regionally, the percentage of extreme precipitation (above 95th percentile) upon total precipitation is lowest in the mountains (TFM, WEG, and EEG) and highest in the 'Saxon Hilly Country' (WSH and ESH).

Seasonal observations (Annex 11) show that during the summer months the absolute thresholds of 10 and 20 mm are more likely to be exceeded as during winter. For the summer half year on average 11.3/ 3.2 days with precipitation above 10/ 20 mm have been observed between 1951 and 2000, while the exceedance frequency for the winter half year is only 6.3/ 1.0 days. Similar seasonal differences also occur in the average magnitudes of the 90th, 95th and 99th

Table 6.16: Annual averages of heavy precipitation indicators for the nine regions (112 stations), timeframe: 1951—2000

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS	Mean
N-10mm	20.3	15.7	25.4	22.7	18.1	12.8	14.6	12.4	15.9	17.5
N-20mm	4.7	3.7	6.3	5.9	4.0	2.9	3.6	2.8	3.8	4.2
N-90P-ad	32.8	34.0	33.9	34.1	33.9	33.6	34.3	33.6	33.9	33.8
N-90P-pd	17.1	17.4	18.8	18.2	17.7	15.5	16.2	15.5	16.6	17.0
N-95P-ad	16.2	16.9	17.3	17.2	17.2	16.9	17.1	16.8	17.1	17.0
N-95P-pd	8.4	8.6	9.6	9.2	9.0	7.9	8.4	7.9	8.5	8.6
N-99P-ad	3.3	3.5	3.7	3.8	3.5	3.6	3.7	3.5	3.6	3.6
N-99P-pd	1.8	1.9	2.0	2.1	2.0	1.7	1.9	1.7	1.9	1.9
Mgt-90P-ad	6.6	5.5	7.6	7.1	6.0	4.7	5.2	4.8	5.6	5.9
Mgt-95P-ad	10.3	8.9	11.8	11.1	9.8	7.9	8.5	7.8	9.0	9.5
Mgt-99P-ad	20.4	19.2	23.5	23.3	20.3	17.5	19.1	17.3	19.2	20.0
Mx-R	38.1	38.9	44.4	44.2	39.8	36.5	39.6	36.4	40.4	39.8
API-95P-ad	18.7	16.8	20.8	20.3	17.7	15.4	16.7	15.3	16.9	17.6
API-95P-pd	23.7	22.3	25.8	25.7	22.6	21.0	22.3	20.8	22.6	23.0
PP-95P-ad	38.1	42.2	38.9	40.4	41.7	44.7	44.3	44.0	42.9	41.9
PP-95P-pd	24.9	28.2	26.8	27.5	27.9	28.3	29.0	27.9	28.1	27.6

Abbreviations of individual indicators are explained in Table 2.5

percentile. The 90th percentile is with 10 mm highest in July in the Erzgebirge regions (WEG and EEG), whereas in the 'Western Saxon Hilly Country' (WSH) and the 'Elbe Mulde Lowlands' the smallest 90th percentile magnitudes of 3.4 mm have been observed in January and February. The lowest 99th percentile value of 7.4 (WSH, February) is still smaller than the annual average of the 90th percentile for region WEG. Although a distinct seasonality is also visible in the monthly data of the maximum daily precipitation, the average half year maxima are almost equal in the mountainous regions (TFM, WEG, and EEG). The average precipitation intensity above the 95th percentile as well as the percentage of precipitation above this threshold upon total precipitation is highest in summer (July, August) and particularly low in winter (February). Due to their definition based on normal precipitation at each station, seasonal and regional differences in the frequency of exceeding percentile thresholds are very small in all months and seasons, but still they are visible with slightly higher frequencies during summer and in the regions with higher average altitudes.

6.3.2 Meteorological Dry Periods

Severe short term drought conditions are described by the meteorological dry period concept. Annually, on average 48 meteorological dry periods (N-DP) with a mean/ maximum duration (Av-DPD/ Mx-DPD) of 15.5/ 22 days are observed within 10 years (Table 6.17). Due to the definition of meteorological dry periods, as a continuous sequence of dry days with daily precipitation less than 1 mm, the average precipitation during such events is only 4.2 mm. About 74 days (N-DP-D) out of 246 dry days (N-DD) per year belong to various meteorological dry periods. Dry periods lasting at least 14 days (N-DP-14) occur about 25 times in 10 years and such events with duration of smallest 21 days (N-DP-21) about 6 times.

Table 6.17: Annual averages of meteorological dry period indicators for the nine regions (105 stations), timeframe: 1951—2000

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS	Mean
N-DD	235.9	247.6	227.6	231.7	244.5	258.9	253.7	259.3	250.5	246.1
N-DP-D	66.9	71.1	57.0	58.7	72.7	85.6	81.3	90.4	80.1	74.4
N-DP/10a	43.9	46.3	37.8	38.9	47.6	54.6	51.8	57.3	50.8	48.0
Av-DPD	15.2	15.3	15.2	15.2	15.1	15.6	15.6	15.8	15.8	15.5
Mx-DPD	21.4	21.6	20.0	20.2	21.5	22.8	23.1	23.4	22.8	22.0
P-DP	3.6	4.4	3.2	3.5	4.3	4.8	4.4	4.8	4.3	4.2
N-DP-14/10a	21.6	23.0	18.7	19.5	24.1	29.8	28.0	31.9	28.1	25.2
N-DP-21/10a	5.3	5.5	4.2	4.1	5.0	7.6	7.2	8.8	6.9	6.2

Abbreviations of individual indicators are explained in Table 2.1

Most frequently, meteorological dry periods occur in the northern lowland and hilly country regions (WSH; ESH, EML, and LAS) matching the higher frequency of dry days in comparison to mountainous regions (TFM, WEG, and EEG, Table 6.17). The regional differences in average dry period duration are very small, just the maximum duration shows a considerable gradient from 20 days in the 'Western Erzgebirge' (WEG) to 23.4 day in the 'Elbe-Mulde Lowlands' (EML). The longest meteorological dry period have been observed at the stations Drebkau (Figure 6.14a) and Oppach in the easternmost region LAS with 66 days (Table 6.18). It lasted from August 17th to October 21st 1959. During that period the majority of stations showed the longest meteorological dry period, lasting for 63 or 64 days from August 17th/ 18th to October 19th 1959. At some stations the dry period of autumn 1959 was interrupted for one day. For instance, at 'Fichtelberg' (WEG) it lasted from August 29th to September 21st and from September 23rd to October 19th. Such small gaps of only a few days between two or more dry events are not visible in most graphical illustrations (Figure 6.14). At station 'Fichtelberg' in region WEG the smallest station value of the longest meteorological dry period was observed with 34 days (Table 6.18) from December 9th 1972 to January 11th 1973.

The seasonal and monthly averages of meteorological dry period indicators are presented in Annex 12. Meteorological dry periods occur with about 28 times in ten years more frequent during the winter half of the year than in the summer half year, where only 20 events within ten years have been observed. March (5.6 events) and October (6.1 events) show the highest frequency of dry events within 10 years and June and July (2.9 dry periods) the lowest. Correspondingly, the number of days belonging to meteorological dry periods is highest in October (10.7 days) and lowest in June (3.7 days). This indicator gives an unbiased estimator of the extent to which a month or season is influenced by meteorological drought events, as each dry period is assigned (with

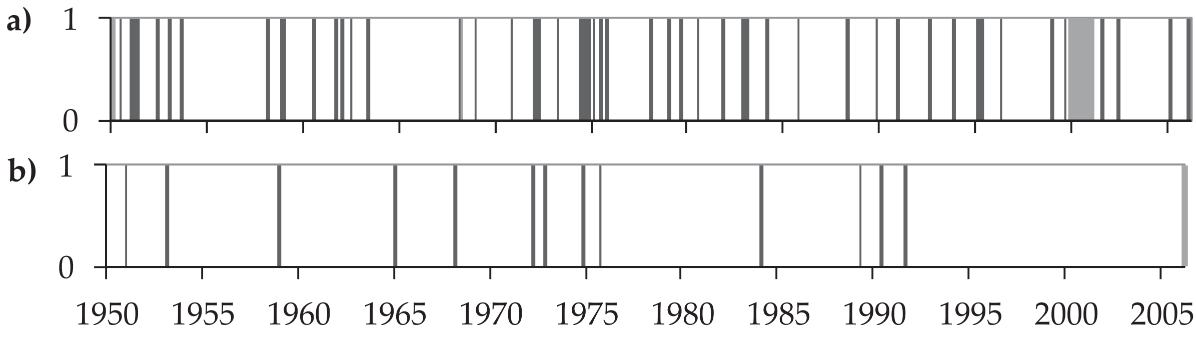


Figure 6.14: Drought occurrence at station a) Drebkau (LAS) and b) Fichtelberg (WEG) for 1951—2006 using the meteorological dry period indicator (dark grey bars: dry periods ≥ 21 days, light grey bars: missing precipitation data)

its occurrence and duration) to the month/ season in which it ends. In the lowland and hilly country (WSH, ESH, EML, and LAS) the seasonal variations in the frequency of meteorological dry periods as well as the number of dry period days are less pronounced than in the mountainous regions (TFM, WEG, and EEG).

The seasonal and regional differences in mean and maximum dry period duration are comparatively low. In February, March, October and November, meteorological drought events last a little bit longer than in the other months. On a monthly basis, the values of mean and maximum duration are almost the same, since two meteorological dry periods that last at least 11 days, occur only very rarely twice a month. Hence, the mean is at the same time the maximum duration of a dry period. For averaging the mean and maximum dry period duration, only those months, seasons or years, respectively, are included that actually were affected by at least one event. Zero values (no meteorological dry period) are only included in the calculation of drought frequency. October is the month that is most affected by meteorological dry periods as in all regions the frequency of dry periods and dry period days as well as their mean and maximum duration are highest amongst all months.

Figure 6.15 shows the timing of meteorological dry periods at all stations on the basis of monthly values, whereby a dry month is displayed if at least 15 days per month belong to a dry period. Similar to monthly drought indicators spatial drought pattern emerge, but the dry periods themselves are much shorter. Due to the downsizing of the temporal scale and the small size of the illustration, single drought events seem to last longer than they really do. As described for Figure 6.14, various meteorological dry periods that are separated by only a few days, are visible as one single drought event. For some months meteorological dry periods have been observed in all regions, while in other months no single meteorological dry period has been observed. The already described higher frequency of dry periods in the lowland and hilly country regions (EML, WSH, ESH, and LAS) in comparison to the Erzgebirge regions (WEG and EEG) is also evident in that illustration.

Table 6.18: Regional averages as well as minimum and maximum station values of the longest meteorological dry period duration [days] observed in 1951—2006

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS
Number of stations	15	15	12	7	5	12	9	12	18
Regional mean	51.3	54.2	45.7	57.4	58.0	54.8	59.0	53.3	55.0
Lowest station value	37	37	34	52	37	37	44	37	37
Highest station value	63	63	63	64	64	64	64	64	66

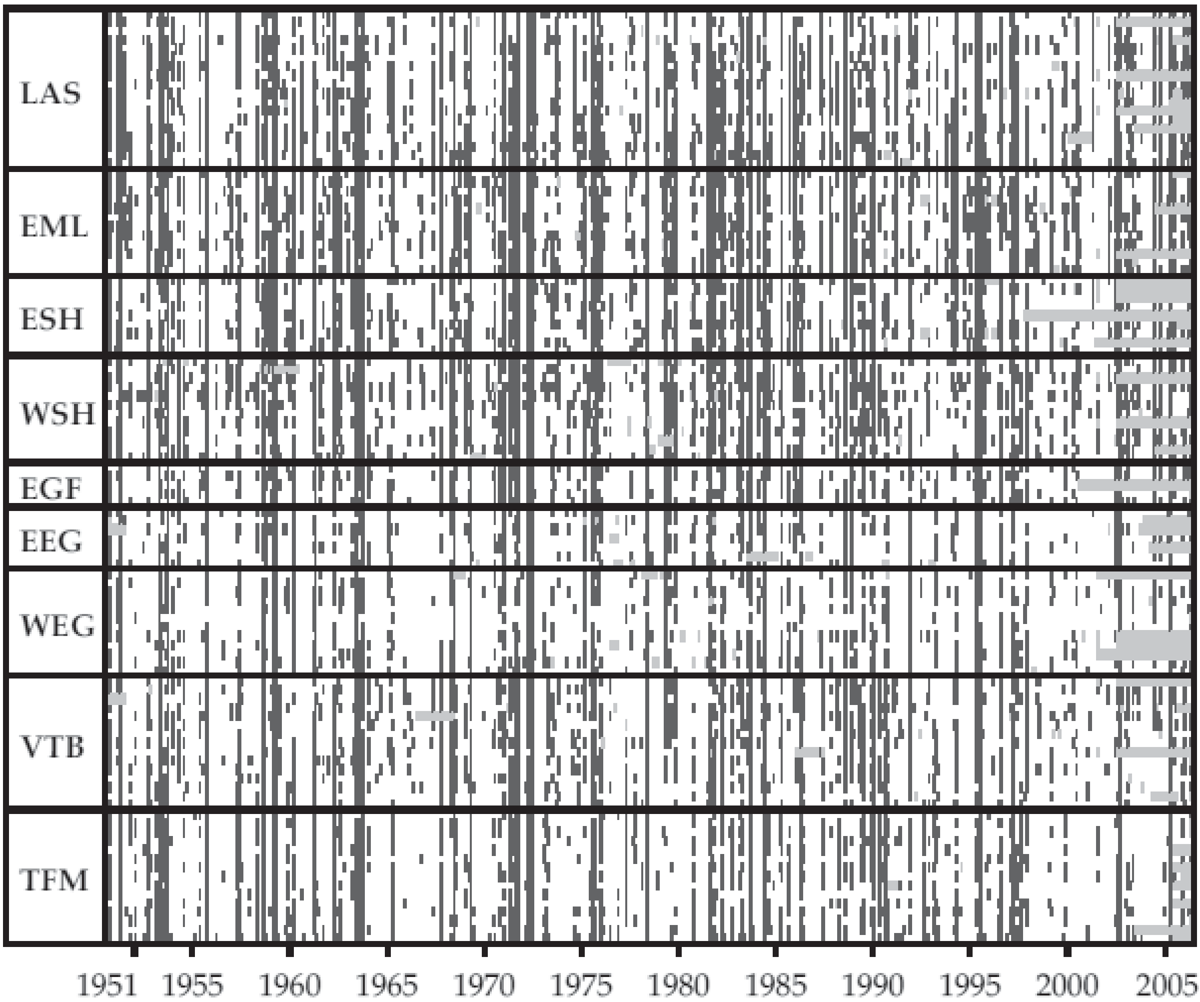


Figure 6.15: Timing of meteorological dry periods (dark grey bars) within the nine regions for 1951—2006 (light grey bars indicate missing precipitation data)

6.3.3 Meteorological Dry Periods with Sliding Thresholds (DPST)

The introduction of a threshold for the termination of meteorological dry periods that depends on the duration of the drought event makes it possible to describe longer term drought conditions (≥ 30 days) based on daily precipitation data. Exemplary; the results for two thresholds are presented – one absolute value (increase by 1mm per day, DPST-1mm) and one defined in relation to normal precipitation (increase by 75% of normal precipitation of 1961—1990, DPST-75%). The use of other thresholds like 0.5 mm or 65% of normal precipitation is possible and has to be adjusted to the scope of application.

Meteorological dry periods with a sliding threshold of 1 mm per day lasting at least 30 days occur on average 23 times in 10 years (N-DPST-1mm/10a) and annually about 162 days belong to such dry periods (N-DPST-1mm-D, Table 6.19). Their mean duration is about 76 days (AvD) and the longest one lasts on average 103 days (MxD). The longest duration of a meteorological dry period with a sliding threshold of 1 mm per day lasted 941 days and has been observed at station Meuselwitz (WSH) from September 24th 1962 to April 21st 1965 (Figure 6.16a, Figure 6.17, Table 6.22). At stations in mountainous regions the longest drought event is frequently shorter than 183 days. At the highest station, Fichtelberg (WEG), the longest dry period lasted only 91 days (Figure 6.16b). Dry events that last at least 91/ 183 days emerge approximately 4.2/ 1.2 times in 10 years and the corresponding number of days belonging to such a dry periods is 72/ 33 days per year averaged over all stations. Annually, about 150 mm precipitation is falling during DPST-1mm droughts, with high regional variations dependent on the differences in dry period duration. The regional differences in the frequency and duration of dry periods are very high as this drought indicator is based on absolute values. Thus, the existence of considerable regional variations in normal precipitation, depending on the orography of the study area lead to a high regional differentiation in the drought characteristic according to this indicator as shown in Figure 6.16 and Figure 6.18a.

Table 6.19: Annual averages of DPST-1mm indices for nine regions (105 stations), timeframe: 1951—2000

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS	Mean
N-DPST-1mm-D-30d	129	164	96	102	143	214	194	217	174	162
N-DPST-1mm-D-91d	44	70	23	24	58	126	92	118	77	72
N-DPST-1mm-D-183d	16	25	4	4	18	72	43	65	38	33
N-DPST-1mm/10a	21.7	24.5	17.2	18.8	21.8	24.4	26.4	26.4	24.6	23.1
AvD-DPST-1mm	61	75	53	56	69	104	80	97	78	76
MxD-DPST-1mm	77	102	62	67	90	137	117	139	110	102
P-DPST-1mm	116	154	88	96	129	199	176	200	161	150
N-DPST-1mm-91d/10a	2.6	4.8	1.5	1.7	3.8	6.7	5.3	6.3	4.5	4.2
N-DPST-1mm-183d/10a	0.6	1.1	0.1	0.1	0.7	2.6	1.5	2.3	1.4	1.2

Abbreviations of individual indicators are explained in Table 2.1

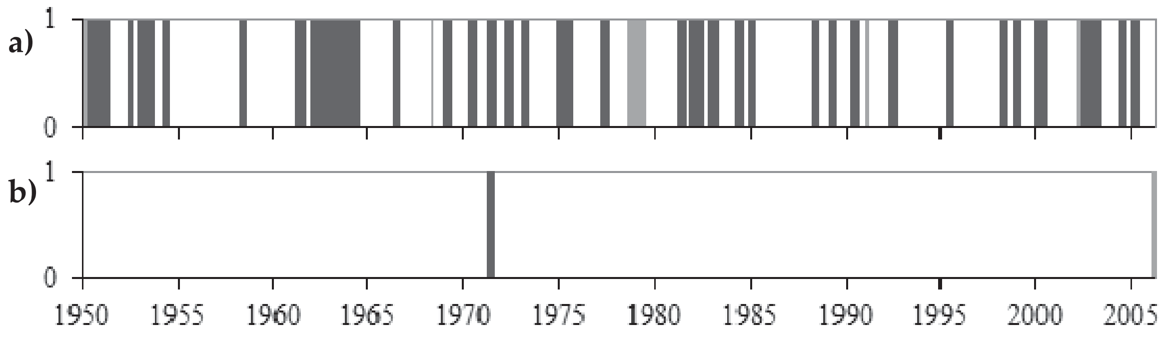


Figure 6.16: Drought occurrence at station a) Meuselwitz (WSH) and b) Fichtelberg (WEG) for 1951—2006 using the DPST-1mm indicator (dark bars: dry periods lasting ≥ 91 days, light grey bars: missing precipitation data)

Figure 6.17 compares the cumulated precipitation during the longest DPST-1mm drought at station Meuselwitz (WSH) to the continually increasing threshold value. It can be seen that slight variations in the size of the threshold or the actual precipitation totals might have lead to a much earlier drought termination.

The DPST-1mm indicator shows some seasonal differentiations in the frequency and duration of dry periods (Annex 13). Most frequently drought events end (the dry periods are assigned to the month in which they are terminated) in April to May and in November and December. The dry period frequency in those months is approximately 2.5 cases within 10 years. For September, the least drought events have been observed with about 1 event in 10 years. In the regions at higher altitudes (TFM, VTB, WEG and EEG) DPDT-1mm dry events occur or end, respectively, more frequent during the winter half of the year, while the drought frequency in the other regions is almost the same in both half years (EGF, WSH, ESH and LAS) or higher during the summer half year (EML).

Longer lasting DPST-1mm dry periods of 91 and 183 days, respectively, occur in the majority of regions most frequent in spring or summer (Annex 13). As the seasonal results of the dry period frequency and duration are strongly biased by the termination date of the particular drought event the number of dry

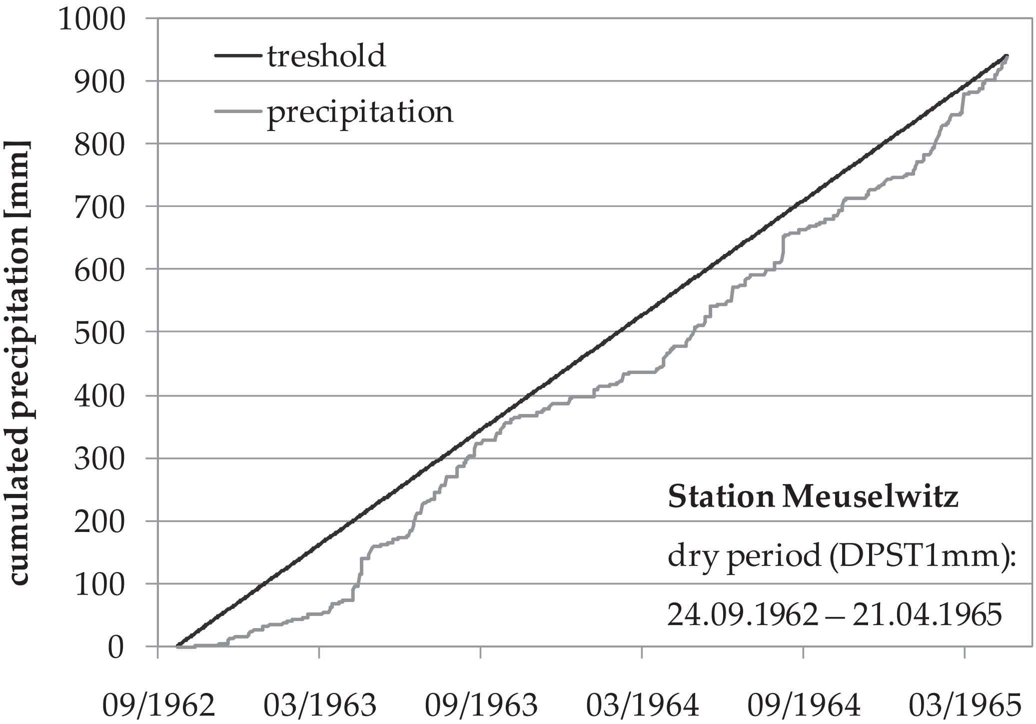


Figure 6.17: Cumulated precipitation during the longest DPST-1mm drought at station Meuselwitz (WSH, 24.09.1962—21.04.1965) in comparison to the DPST-1mm threshold

period days is used to evaluate how much seasons and single months are concerned by drought. Using this index March and October are the most drought affected months with an average of about 18 dry period days, whereas the summer months June to August are the least affected ones (only 7 to 8 days). This is likely due to the summerly precipitation characteristics with more frequent convective heavy precipitation events that might terminate a drought or prevent its onset. This is supported by the comparatively high precipitation totals of dry period days during the summer months. On average, the highest dry period precipitation totals have been observed in May and June (approx. 80 mm) and the lowest ones in October (approx 38 mm). Nevertheless, there are great regional variations that may be attributed to the absolute thresholds used by the DPST-1mm concept.

To account for regional differences in normal precipitation and to ensure the comparability of trends calculated in section 7.2, a sliding relative threshold of 75% of daily normal precipitation is used additionally. The dependence of the threshold's magnitude on normal precipitation is displayed in **Table 6.20**. For the northern lowlands the threshold almost equals 1 mm. Therefore, the results of both DPST indicators are most similar for the regions WSH, ESH, EML and LAS. In contrast, the value by which the threshold is increased for every further dry period day may be twice as high for stations in the low mountain ranges. Thus, the results for the mountainous regions TFM, WEG and EEG are most different for the two DPST concepts.

Dry periods, defined on the basis of a moving 75%-threshold, have on average a similar frequency like those with an absolute threshold of 1 mm per day (Table 6.21), while longer lasting droughts of 91 or 183 days duration, respectively, occur with 8.2 and 3.2 times per 10 years more frequent. The mean and

Table 6.20: Threshold magnitudes of the DPST-75% indicator for different annual precipitation totals

Annual precipitation total [mm]	75%-threshold value [mm/d]	threshold's magnitude [mm] for a drought duration of		
		91 days	183 days	365 days
500	1.03	93.5	188.0	375
600	1.23	112.2	225.6	450
700	1.44	130.9	263.2	525
800	1.64	149.6	300.8	600
900	1.85	168.3	338.4	675
1000	2.05	187.0	376.0	750
1100	2.26	205.7	413.6	825
1200	2.47	224.4	451.2	900

maximum duration of dry periods is on average almost twice as high as for the 1-mm-threshold. Correspondingly, more days per year belong to dry periods lasting at least 30, 91 or 183 days and the precipitation falling within dry periods is with 363 mm per year considerably higher. The longest DPSP-75%-dry-period lasted for 1794 days from July 29th 1961 to June 26th 1966 and has been observed at station 'Greiz-Dölau' in region 'Vogtland and Thuringian Basin' (VTB).

Seasonally, the longest dry periods identified by the DPST-75% indicator have been observed during summer and late spring with approximately 120 to 170 days averaged over all regions (Annex 14). Those months also show the highest frequency of ending dry periods (2.0 to 2.8 cases per 10 years) and the highest precipitation totals during drought events. The drought frequency is also high in December (2.5 events in 10 years) that show quite low average drought durations (approx. 80 days). Long dry periods (≥ 91 and ≥ 183 days) occur or end, respectively, considerably more often during the summer half year than during winter, whereas they have the lowest frequency in autumn. Despite the high drought frequencies and durations attributed to the summer months, those months are least drought affected when looking at the days attributed to DPST-75% dry periods. Over all regions, 15 to 19 days are attributed to DPST-75% droughts for June to September, while all other months are affected by 22 to 26 drought days. The same is true for long dry periods lasting more than 91 or 183 days, respectively. Particularly in July and August very few days are attributed to dry periods.

Table 6.21: Annual averages of indices based on the concept of Meteorological Dry Periods with a sliding threshold of 75% of daily normal precipitation for nine regions (105 stations); 1951—2000

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS	Mean
N-DPST-75%-D-30d	259	260	254	255	260	263	268	264	262	261
N-DPST-75%-D-91d	184	193	171	164	175	194	182	182	181	182
N-DPST-75%-D-183d	126	135	102	101	129	142	131	127	125	125
N DPST-75%/10a	22.9	21.8	24.9	25.4	24.3	21.9	24.6	24.3	23.8	23.5
AvD-DPST-75%	144	142	119	118	123	152	131	135	139	136
MxD-DPST-75%	201	204	175	173	192	200	194	195	189	193
P-DPST-75%	426	347	456	420	372	306	328	302	334	363
N-DPST-75%-91d/10a	7.9	8.5	8.6	8.0	7.8	8.2	8.1	8.1	8.0	8.2
N-DPST-75%-183d/10a	3.5	4.1	3.2	3.1	4.2	4.4	4.1	3.9	3.7	3.8

Abbreviations of individual indicators are explained in Table 2.1

The regional characteristic maximum drought duration of both DPST indicators and their dependence on normal precipitation is displayed in Table 6.22. Due to the high precipitation totals in the 'Western Erzgebirge' (WEG) the 75%-threshold of daily normal precipitation is highest and the maximum duration of dry periods with an absolute threshold of 1 mm lowest out of all regions. The lowest 75%-thresholds have been observed in the regions with lowest average altitudes EML and WSH. Hence those regions show the longest DPST-1mm dry periods.

Quite interesting are the statistics for the DPST-75% concept, the thresholds of which vary in dependence of normal precipitation. Although the 75%-threshold of the regions VTB and LAS is of same magnitude, both regions differ considerably in the maximum dry period durations according to the DPST-75% concept (Table 6.22). On average, the longest droughts have been observed for region VTB, while the average duration of dry periods is lowest in region LAS. Region VTB is in the lee of several low mountain ranges and might therefore be less affected by heavy precipitation events or periods that could terminate the drought. Nevertheless, the regions VTB and LAS are very similar in the characteristics of heavy precipitation indices as well as in their annual precipitation cycles. Just the regionally averaged maximum daily precipitation is higher in LAS than in VTB.

Table 6.22: Relation between the threshold's magnitude (75% of daily normal precipitation) of the DPST-75% indicator and the maximum duration of dry periods according to the DPST-1mm and DPST-75% concepts (grey background colours: region with highest and lowest value, respectively); 1951—2006

	Magnitude of 75%-threshold [mm]			Longest Meterological Dry Period [days]					
				75%-Pd-threshold			1-mm-threshold		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
TFM	1.62	1.23	2.27	735	542	993	266	106	334
VTB	1.35	1.20	1.60	960	487	1794	326	145	513
WEG	1.84	1.56	2.29	697	474	890	154	91	292
EEG	1.71	1.52	1.86	855	492	1425	191	95	322
EGF	1.45	1.29	1.57	788	543	1026	304	205	414
WSH	1.17	0.98	1.32	793	511	1368	470	257	941
ESH	1.25	1.11	1.36	749	537	960	426	304	687
EML	1.16	1.05	1.28	844	565	980	520	257	687
LAS	1.33	1.13	1.69	674	381	917	379	192	686
all stations	**1.42**	**0.98**	**2.29**	**783**	**381**	**1794**	**344**	**91**	**941**

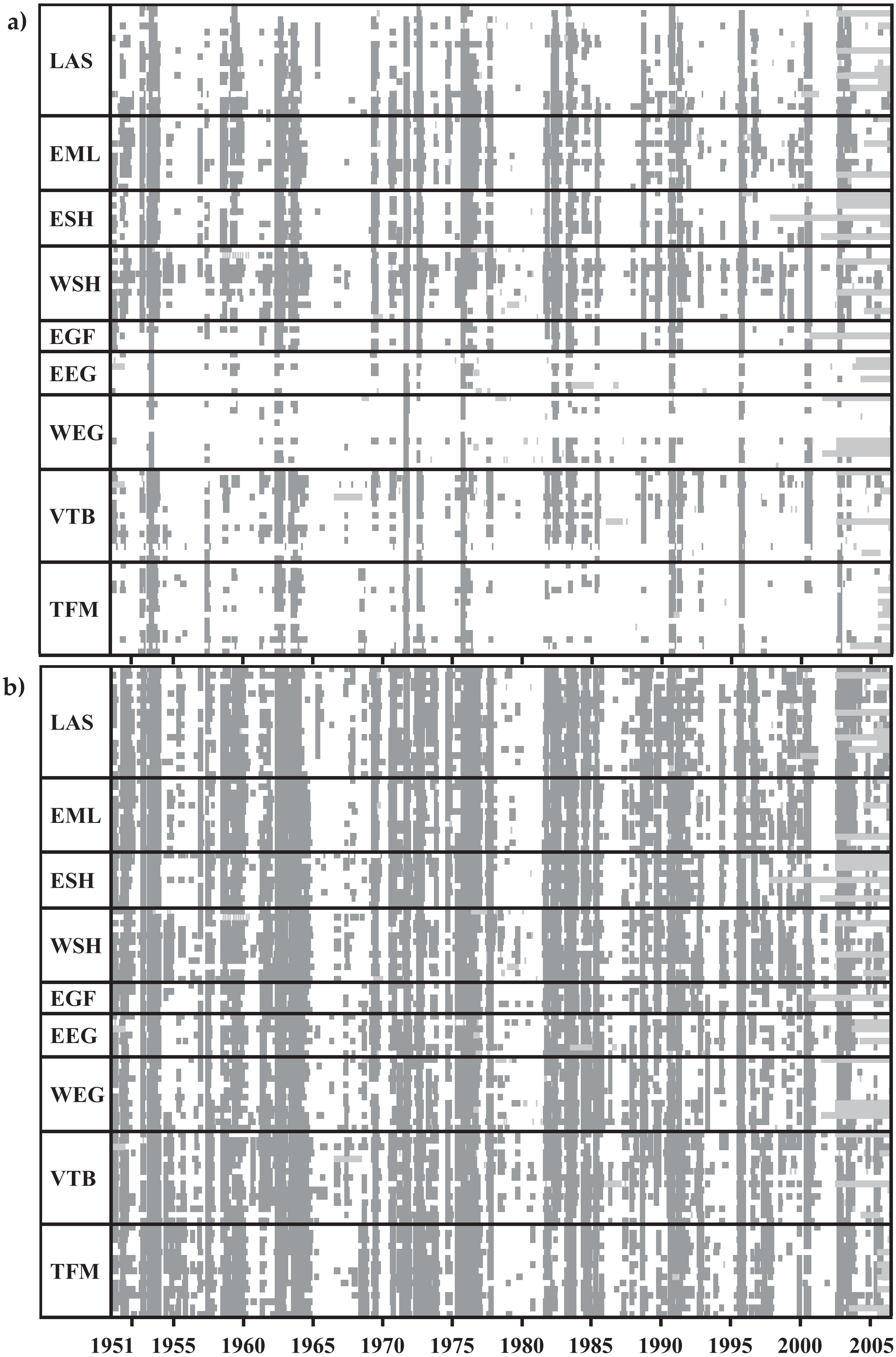


Figure 6.18: Timing of drought events lasting at least 91 days identified by the DPST-indicators for a) the absolute threshold of 1mm and b) the relative threshold of 75% of normal precipitation for 1951—2006 (light grey bars indicate missing data)

Printing the occurrence of DPST-1mm drought events lasting at least three months (DPST-1mm-91d) of all stations into on picture (Figure 6.18a), reveals some drought pattern similar to those observed for decile dry periods. The minimum duration of three months was chosen to allow comparison to decile droughts, calculated based on three-month totals. The timing of DPST-75% dry periods, lasting at least three months (DPST-75%-91d), is displayed in Figure 6.18b. Like decile droughts, DPST dry periods very often occur simultaneously at the majority of stations, indicating that some large-scale atmospheric circulation pattern not only trigger monthly, but also daily precipitation extremes. However, the regional differences in the DPST-1mm-91d duration and frequency are much higher than compared to decile or DPST-75%-91d droughts. Generally, the average DPST-1mm-91 drought is considerably shorter than decile dry periods, whereas more months seem to be affected by DPST-75%-91d than by decile droughts. This suggests that the severity (departure from normal water availability) of DPST-1mm-91 droughts is higher, and analogously for DPST-75%-91d dry periods lower, than the one of decile droughts.

Like for decile dry periods, periods with clustered DPST droughts and other periods with almost no drought events within the entire study area have been observed. Periods with clustered DPST occurrence are 1951—1954, 1957—1964, 1970—1978 and 1982—1986. Beyond 1990 the DPST droughts occur less clustered and on average DPST-75%-91 droughts affect a smaller percentage of stations. Thereby the periods without major DPST drought conditions are shorter at the end of the study period.

6.3.4 Resume

Frequency, severity and persistence of daily precipitation extremes were characterised using several 'Heavy Precipitation Indices' (HPI) and meteorological dry period concepts (DP and DPST). Regional differences in the frequency of exceeding the absolute thresholds of 10 mm and 20 mm, respectively, as well as in the magnitude of percentile thresholds, follow the differences in average precipitation totals and thus are mainly due to the orographic structure of the study area. The seasonal differences follow the annual precipitation cycle. As expected, the exceedance frequency of the relative percentile thresholds was spatially and seasonally less variable than for absolute thresholds. The threshold of 10 mm daily precipitation was exceeded about four times more often as compared to 20 mm. The exceedance frequency for the percentile thresholds ranged from 2 times per year for the 99th percentile calculated with approach "pd" to 34 times for the 90th percentile computed with approach "ad". The maximum daily precipitation total per year was on average 40 mm, with the highest values in the Erzgebirge regions.

Different dry period indicators, based on absolute (DP, DPST-1mm) and relative thresholds (DPST-75%), were studied, yielding different dry period durations. Using a constant threshold of 1 mm, that is not exceeded at a single dry period day, delivered very short meteorological dry periods (DP) of on average 15 days. Raising the threshold for dry period termination in dependence on the drought's duration (DPST), delivered considerably longer dry periods that were rather comparable to decile droughts than DP. Two thresholds were compared for DPST dry periods, one absolute (increase by 1 mm per dry period day, DPST-1mm) and one relative threshold (increase by 75% of daily normal precipitation per dry period day, DPST-75%). DPST-1mm dry periods lasted on average 76 days, while the average DPST-75% drought continued for 136 days. DP-events were with 48 times in 10 years about twice as frequent as DPST droughts, occurring about 23 times in 10 years, independent from the chosen threshold. Regional differences in dry period duration and frequency were more pronounced for the indicators based on absolute thresholds than for the relative one, with less frequent and shorter droughts in the mountainous regions.

All dry periods, based on daily precipitation data, showed similar spatial drought pattern with periods of clustered dry period occurrence and a very high spatial drought coverage simultaneously to decile droughts. Large-scale atmospheric circulation pattern seem not only to trigger monthly, but also daily precipitation extremes. Nevertheless, there were also considerable differences in drought occurrence of different dry period indicators, due to the different time scales addressed by individual indicators and the "absolute nature" of the DP and DPST-1mm concepts.

7 Changes in Saxon Precipitation Characteristics

7.1 Variations in the General Characteristics of Precipitation

Changes in the general precipitation characteristics, based on monthly precipitation totals have been studied within the project EXTROSA III (Petzold et al. 2007; Hänsel et al. 2009) for the 'Saxon State Agency of Environment and Geology'. The analysis was done on the basis of 238 rain gauge stations in Saxony and surroundings that were taken from the Saxon Climate database (Franke et al. 2004). As this data base is more comprehensive than the one used for the bigger part of this study, the results presented in this section are based on the EXTROSA III data.

Table 7.1 gives an overview about the data availability within the nine regions for individual periods used for trend analysis within this section. For secular trends regional analyses do not seem to be reasonable due the poor data availability within individual regions.

Table 7.1: Number of stations with at least 90% data availability for individual periods

Region	1901–2000	1901–2006	1931–2000	1931–2006	1941–2000	1941–2006	1951–2000	1951–2006
TFM	0	0	5	5	10	10	11	11
VTB	1	1	4	4	6	6	27	24
WEG	2	2	2	2	3	3	39	34
EEG	2	1	10	7	10	8	27	24
EGF	2	1	4	3	5	3	14	9
WSH	2	2	7	7	8	8	20	17
ESH	2	2	3	3	5	3	23	19
EML	1	1	5	5	4	4	21	19
LAS	3	3	11	7	12	10	41	38
Total	**15**	**13**	**51**	**43**	**63**	**55**	**223**	**195**

7.1.1 Trends of Precipitation Totals

Annual precipitation totals show spatially and temporally heterogeneous trends. This is shown at the example of three stations belonging to different regions; their annual precipitation time series with linear trends for individual periods are displayed in Figure 7.1. Precipitation increases for all analysed periods have been observed for station 'Rehau' in the 'Thuringian-Franconian Mountains' (TFM). A trend reversal from precipitation increases for the longest period to precipitation decreases in recent times becomes visible at station 'Fichtelberg' in the 'Western Erzgebirge' (WEG). Negative precipitation trends in all periods occur in Eastern Saxony, e.g., at station 'Görlitz' (LAS). Similar tendencies may be found at other stations in those regions, but also dissimilar trend characteristics are possible. This depends mainly on the relation of precipitation increases and decreases during different parts of the year. Generally, a West-East gradient of long-term precipitation trends is visible in the data with precipitation increases in the (South)-Western parts of the study area and decreasing annual precipitation totals in the Eastern and Northern parts.

Generally, the regionally averaged annual precipitation trends (Table 7.2) are quite small in comparison to seasonal trends due to opposite trend directions at individual stations and within the year (Figure 7.2). Thus, changes in the annual precipitation patterns were also analysed for half years, seasons, as well as on a monthly basis (Table 7.3; Figure 7.4).

Table 7.2: Linear regional trends [%] of annual precipitation totals for individual periods

	1901 – 2000	**1901 – 2006**	**1931 – 2000**	**1931 – 2006**	**1941 – 2000**	**1941 – 2006**	**1951 – 2000**	**1951 – 2006**
TFM			9.4	11.6	13.4	14.8	11.8	13.2
VTB	6.5	5.8	0.2	1.0	7.8	8.1	1.9	4.0
WEG	-10.7	-8.3	-5.9	-2.5	-2.2	1.9	-1.7	3.2
EEG	-6.4	-13.2	-0.6	-3.5	2.7	0.1	-0.8	1.9
EGF	-11.5	-14.7	-3.3	-2.6	0.0	5.2	1.8	6.6
WSH	-3.8	-2.3	-0.7	1.7	2.0	4.9	0.2	2.7
ESH	-15.2	-12.9	-12.3	-8.3	-3.0	-4.3	-1.6	0.0
EML	15.0	15.3	-1.3	0.2	-1.3	2.4	-3.5	1.7
LAS	-9.9	-9.9	-2.9	-2.0	1.5	1.2	-1.4	-0.9

relative linear trends: -5% to 0% | 0% to 5% | < -5% | > +5%

The magnitude of annual trends is highest for the longest periods (1901—2000 and 1901—2006) within all regions. This is probably due to the poor data availability during that time (Table 7.1). Only one to three stations have been available in each region for generating the "regional average". For those periods regional trend averages do not make much sense (it would be better to examine the average over the whole study area or single station trends), but they

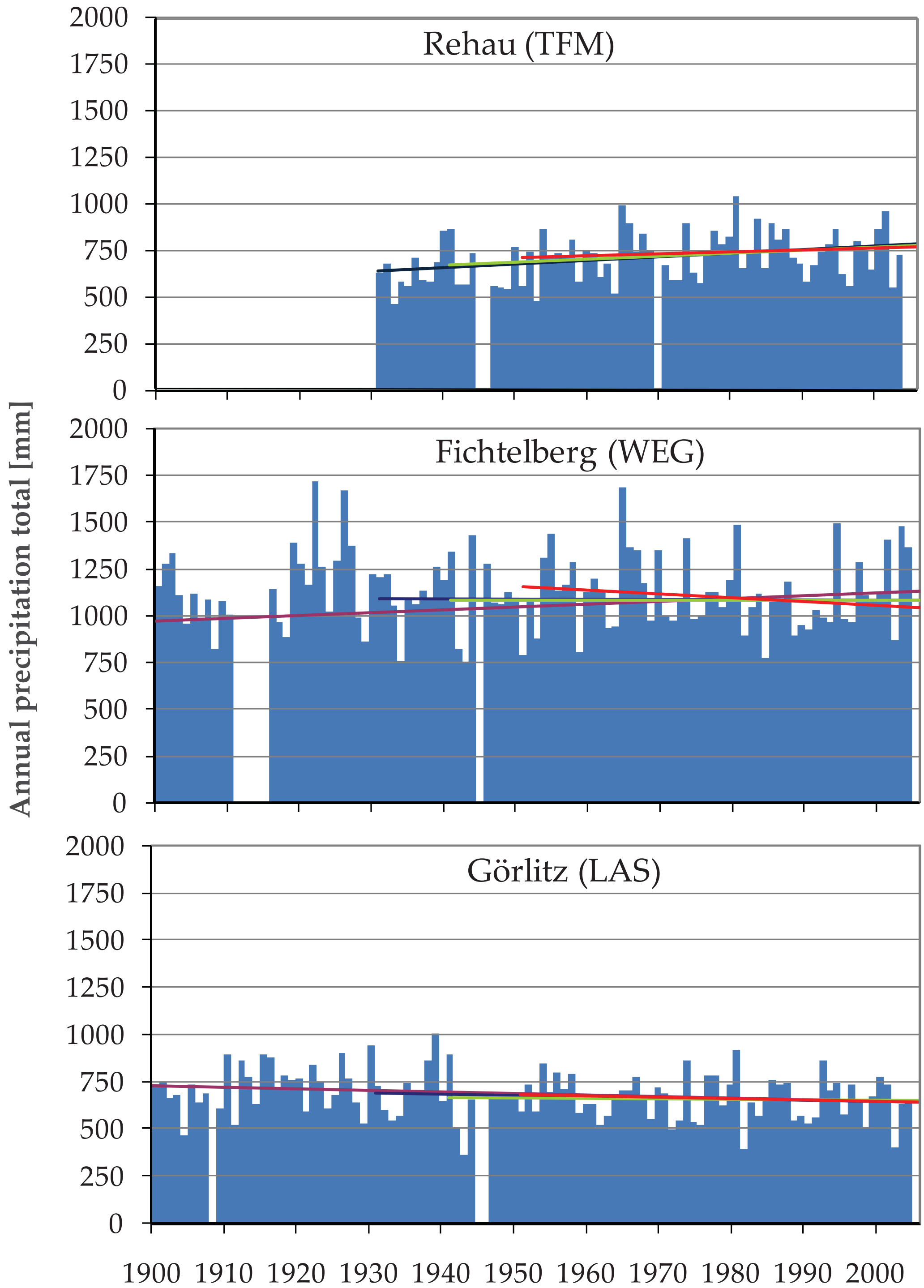


Figure 7.1: Annual precipitation time series with linear trends for 1900—2006 (purple), 1931—2006 (blue), 1941—2006 (green) and 1951—2006 (red) for three stations in three different regions

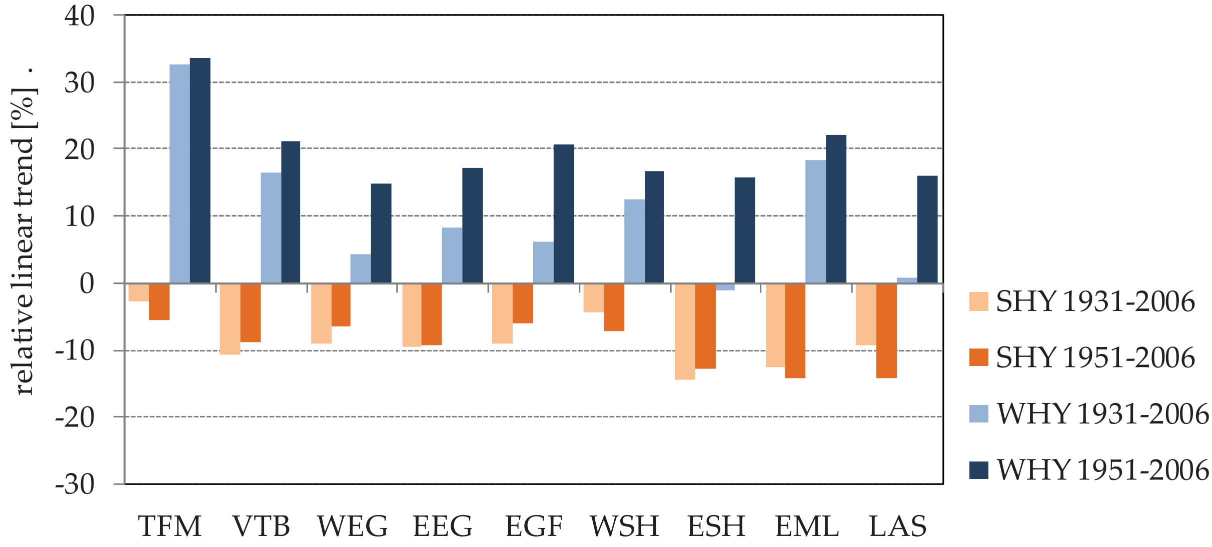


Figure 7.2: Average half year precipitation trends of different regions for the periods 1931—2006 and 1951—2006

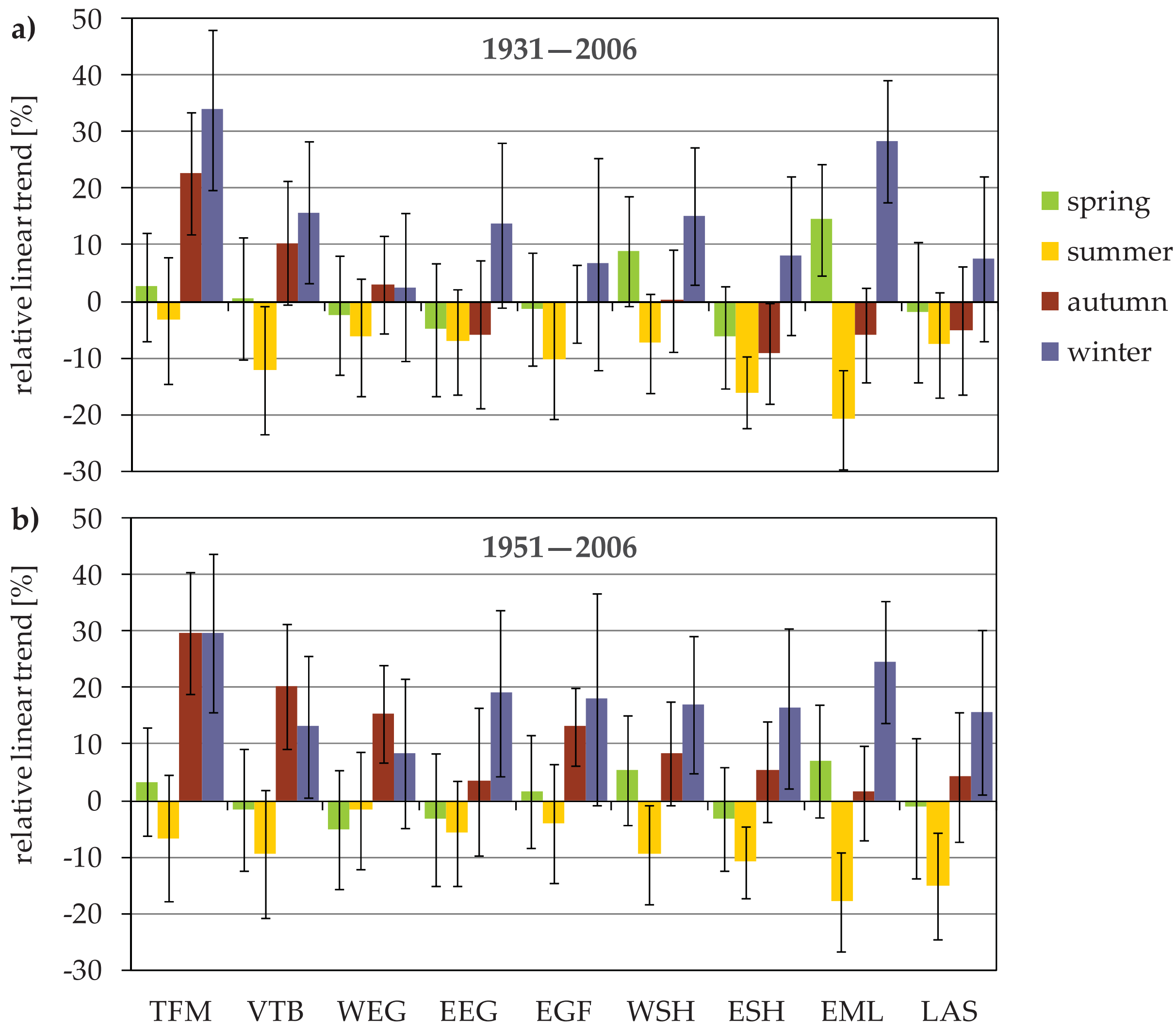


Figure 7.3: Average seasonal trends with standard deviation of different regions for the periods a) 1931—2006 and b) 1951—2006

allow at least a constricted comparison to the regional trends of other periods. The frequency of positive and negative station trends for the whole study area is displayed in Figure 7.4 for different periods. Most stations/ regions show precipitation decreases for centennial time scales, whereas in recent times more precipitation increases were observed.

Regarding the half years, winter shows a positive precipitation trend in almost all regions whereas precipitation decreased in the summer half year for the timeframes 1951—2006 and 1931—2006 (Figure 7.2). The trends of the summer half year for the two different time intervals are quite similar within the regions. The winter trends of the shorter period 1951—2006 are generally higher than those of the longer interval 1931—2006. The 1930s have been a quite wet period during winter and thus suppressed the positive precipitation trend.

Table 7.3: Monthly, seasonal and annual precipitation trends of nine different regions for the period 1951—2006

	TFM	VTB	WEG	EEG	EGF	WSH	ESH	EML	LAS
Year	13.2	4.0	3.2	1.9	6.6	2.7	0.0	1.7	-0.9
SHY	-5.7	-9.0	-6.4	-9.4	-6.1	-7.2	-12.9	-14.2	-14.2
WHY	33.8	21.1	14.9	17.1	20.7	16.8	15.9	22.0	15.9
Spring	3.4	-1.5	-5.1	-3.3	1.7	5.4	-3.2	7.1	-1.2
Summer	-6.7	-9.4	-1.7	-5.8	-4.0	-9.6	-10.9	-17.9	-15.1
Autumn	29.8	20.3	15.3	3.4	13.2	8.4	5.3	1.5	4.3
Winter	29.8	13.3	8.4	19.1	18.0	17.0	16.4	24.7	15.7
Jan	33.3	-2.3	-8.2	6.0	-0.1	-3.0	5.0	14.2	9.2
Feb	32.6	17.8	15.2	30.3	28.4	20.6	21.9	27.4	23.9
Mar	45.6	39.2	33.4	32.7	38.3	37.1	34.4	48.5	41.4
Apr	-20.7	-28.5	-30.0	-37.1	-28.6	-6.2	-30.3	-12.7	-29.0
May	-14.1	-12.8	-16.3	-4.4	-2.5	-8.5	-10.9	-9.9	-11.2
Jun	-15.5	-26.8	-12.2	-15.3	-19.4	-33.4	-20.0	-35.4	-17.9
Jul	0.2	-7.3	-27.3	-37.6	-16.5	5.6	-31.4	-16.0	-37.6
Aug	-5.0	6.8	40.9	39.3	26.4	-1.6	21.6	-2.9	12.5
Sep	20.5	12.4	7.9	-6.8	3.6	3.7	-8.1	-3.7	-1.6
Oct	30.4	-8.5	-17.8	-28.8	-16.5	-32.0	-25.5	-25.4	-19.8
Nov	38.1	57.1	55.6	46.0	56.8	52.6	50.1	33.0	31.9
Dec	20.1	21.8	18.7	19.1	23.5	29.7	18.5	25.4	12.4

relative linear trend:

0 to 5%	-5% to 0
5% to 15%	-15% to -5%
15% to 25%	-25% to -15%
> 25%	< -25%

A distinct annual precipitation increase could be monitored for the 'Thuringian-Franconian Mountains' only (TFM) (Figure 7.2; Table 7.2, Table 7.3). The annual trends of the other regions are quite indifferent as are the spring (MAM) trends of all regions (Figure 7.3). Those indifferent spring trends are a

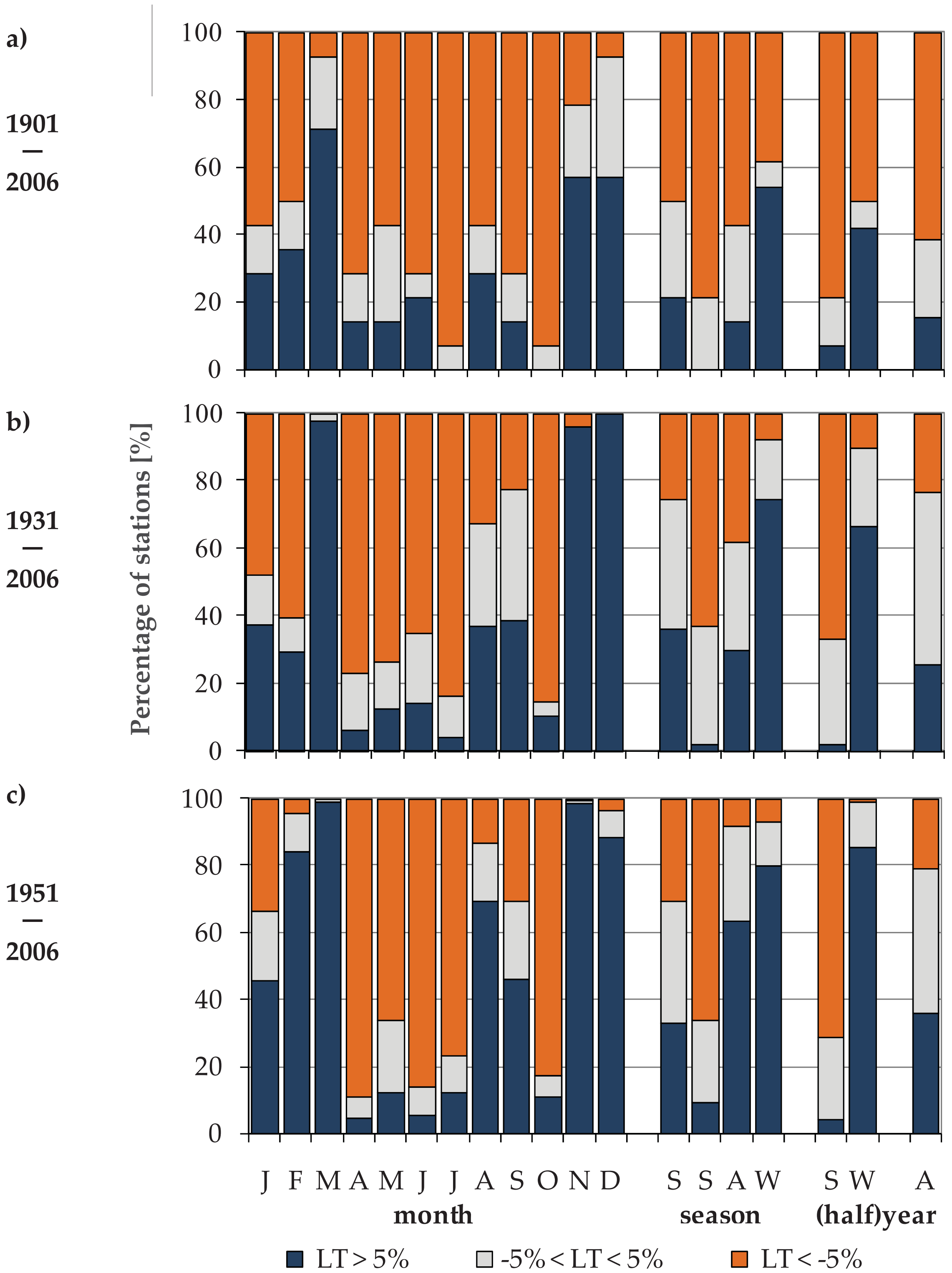


Figure 7.4: Spatial homogeneity of monthly, seasonal and annual precipitation trends for a) 1901—2006, b) 1931—2006 and c) 1951—2006

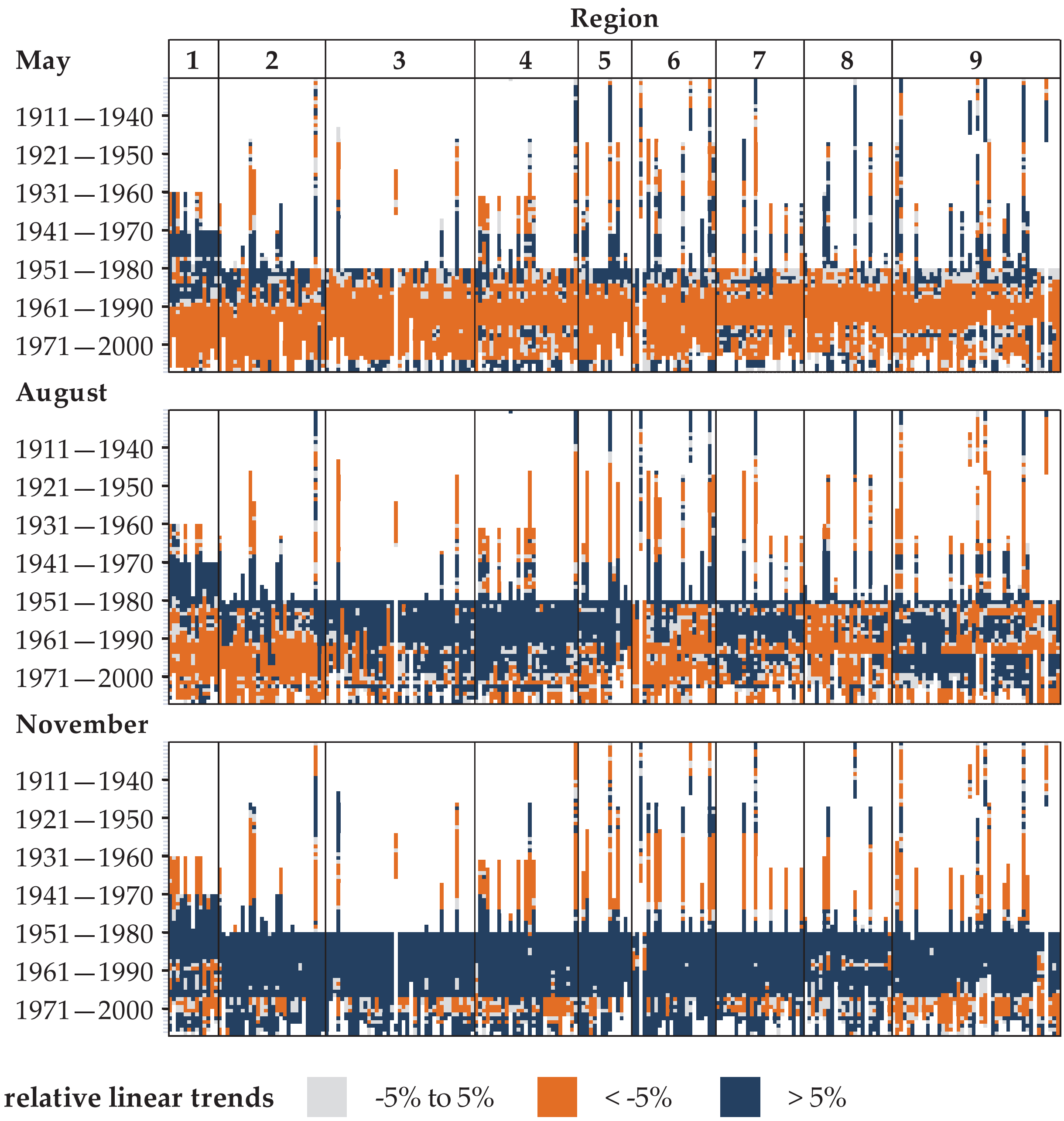
result of the different trend directions in the spring months with very high precipitation increases in March and strong negative trends in April and May (Table 7.3). In summer (JJA), all regions show an average precipitation decrease that is most pronounced in the agriculture dominated regions EML (Elbe-Mulde Lowlands) in the North and in the eastern regions ESH (Eastern Saxon Hilly Country) and LAS (Lausitz and Spreewald; Figure 7.3; Table 7.3). Autumn (SON) and winter (DJF) became wetter in all regions with the highest increases in region TFM. Winter precipitation increases are also quite high in region EML for periods 1931—2006 and 1951—2006. When looking at monthly trends, March and November stand out by very high precipitation increases between 1951 and 2006 (Table 7.3). In all regions precipitation also increased in February and December. This becomes also visible on a station level. Almost all stations show positive precipitation trends above 5% in March and November and in February and December; only few stations show negative or just small trends (Figure 7.4).

During the 1st vegetation period (April to June), and in most regions also in July and October, the precipitation decreases are most pronounced (Table 7.3). This is also true on a station basis. Figure 7.4 shows the highest percentage of stations with negative precipitation trends in the months April to July and October. The ‘Thuringian-Franconian Mountains’ (TFM) in the southwest of the study area is the only region with a strong positive October trend (Table 7.3). This region generally behaves different from the other regions.

7.1.2 Spatiotemporal Characteristics of Precipitation Tends

An overview on the temporal and spatial representativeness of the precipitation trends is given by Figure 7.5 and Annex 15. The illustrations show the trend direction for each 30-year-period from 1901—1930 to 1977—2006 for each station within the nine regions. Three months have been chosen to display different trend signatures. These are May, as an example for decreasing precipitation trends in 1951—2006 in all regions, August as an example for indifferent regional trends, and November with a strong precipitation increase.

In May, most stations show negative 30-year trends as of 1955 – single stations already since 1951. Only in the ‘Thuringian-Franconian Mountains’ (TFM) and ‘Vogtland and the Thuringian Basin’ (VTB), the negative trends start in the 1960s. Since about 1940, precipitation increases have been observed for all regions. Before that time, the trend behaviour of the different regions does not give a clear picture. At the end of the studied timeframe, the trends in almost all regions switch to positive signs.



Regions: 1/TFM, 2/VTB, 3/WEG, 4/EEG, 5/EGF, 6/WSH, 7/ESH, 8/EML, 9/LAS

Figure 7.5: Moving 30-year-precipitation-trends (relative linear trends) for May, August and November for the periods 1901—1930 to 1977—2006

August predominantly shows precipitation decreases since 1951 in the regions TFM, VTB, WSH and EML, but the trends are not as temporally stable as in May (Figure 7.5). Those four regions extend from the Southwest to the North of the study area. The other regions from the Erzgebirge (regions WEG and EEG) in the South to region LAS (Lausitz and Spreewald) in the Northeast of study area predominantly show precipitation increases since the 1940s. Since about 1910 until the 1940, negative 30 year trends dominate the picture.

The 30-year trends of November are most homogeneous within all regions out of the three months compared in Figure 7.5. For the time intervals 1921—1950 to the 30-year trends, starting in the 1940s, precipitation decreases have been observed in all regions. Positive trends predominately occur since that time and until the end of the study timeframe –interrupted by a narrow band of small or negative trends at about the interval 1971—2000.

All stations show positive as well as negative trends for all months and seasons (Annex 15). This reflects the natural variability of precipitation and restricts the significance of short term precipitation trends. In many intervals, especially in May and November, those trend directions are identical for most stations. The spatial representativeness of the trends seems to be quite high. Those patterns suggest that there exist some larger scale precipitation trigger(s).

According to the monthly trend patterns, the regions TFM and VTB behave similar. The trend patterns of the 'Eastern Erzgebirge' (EEG) are in some months, like May more similar to the 'Eastern Saxon Hilly Country' (ESH) than to the 'Western Erzgebirge' (WEG) which itself shows similarities to the 'Erzgebirge Foreland' (EGF) and the 'Western Saxon Hilly Country' (WSH). Generally, those trend patterns support the chosen classification into sub-regions.

7.1.3 Changes in the Annual Precipitation Cycle

Changes in the annual precipitation cycle are triggered by opposite monthly precipitation trends already described in sub-section 7.1.1. For the periods 1931—1955, 1956—1980 and 1981—2005, the average precipitation totals within the nine regions are displayed in Annex 16 and Figure 7.6. For regional averaging only those stations with more than 66.7% data availability within all three periods were included. At least five stations have to meet these criteria to compute the regional average. All regions apart from the 'Western Erzgebirge' (WEG) fulfilled those criteria for all three periods. For region WEG, changes in the regional annual precipitation cycles are therefore only presented for the periods 1956—1980 and 1981—2005 with much better data availability.

The shifts in the annual precipitation cycles are quite similar within individual regions (Annex 16). Only the 'Thuringian-Franconian Mountains' (TFM) show some slight differences in the precipitation tendencies, but the general shifts described here are similar to the other regions. In all regions, a distinct summer precipitation maximum in July can be found for period 1931—1955, whereas the summer maximum of period 1956—1980 is evenly over all three summer months. In 1981—2005 there is a distinct July maximum again, but not as high as for the first period. August precipitation is in the recent period higher than the one of June and in some regions (EEG, ESH and LAS) almost as high as in July. Thus, the summer maximum seems to have shifted from early (June, July) to late (July, August) summer. The winter maximum of period 1931—1955 has been in January to February. It is lower than the winter maximum of the two later periods which has shifted to December. Particularly in region TFM the winter and summer maximum converge – the summer maximum is decreasing slightly and the winter maximum is getting higher.

Changes in the annual precipitation cycle are also visible in the precipitation minima that occurred within the earliest period in all regions in March and December (Figure 7.6, Annex 16). The precipitation minima shifted to February and October in the last period of 1981—2005. Those minima are smaller

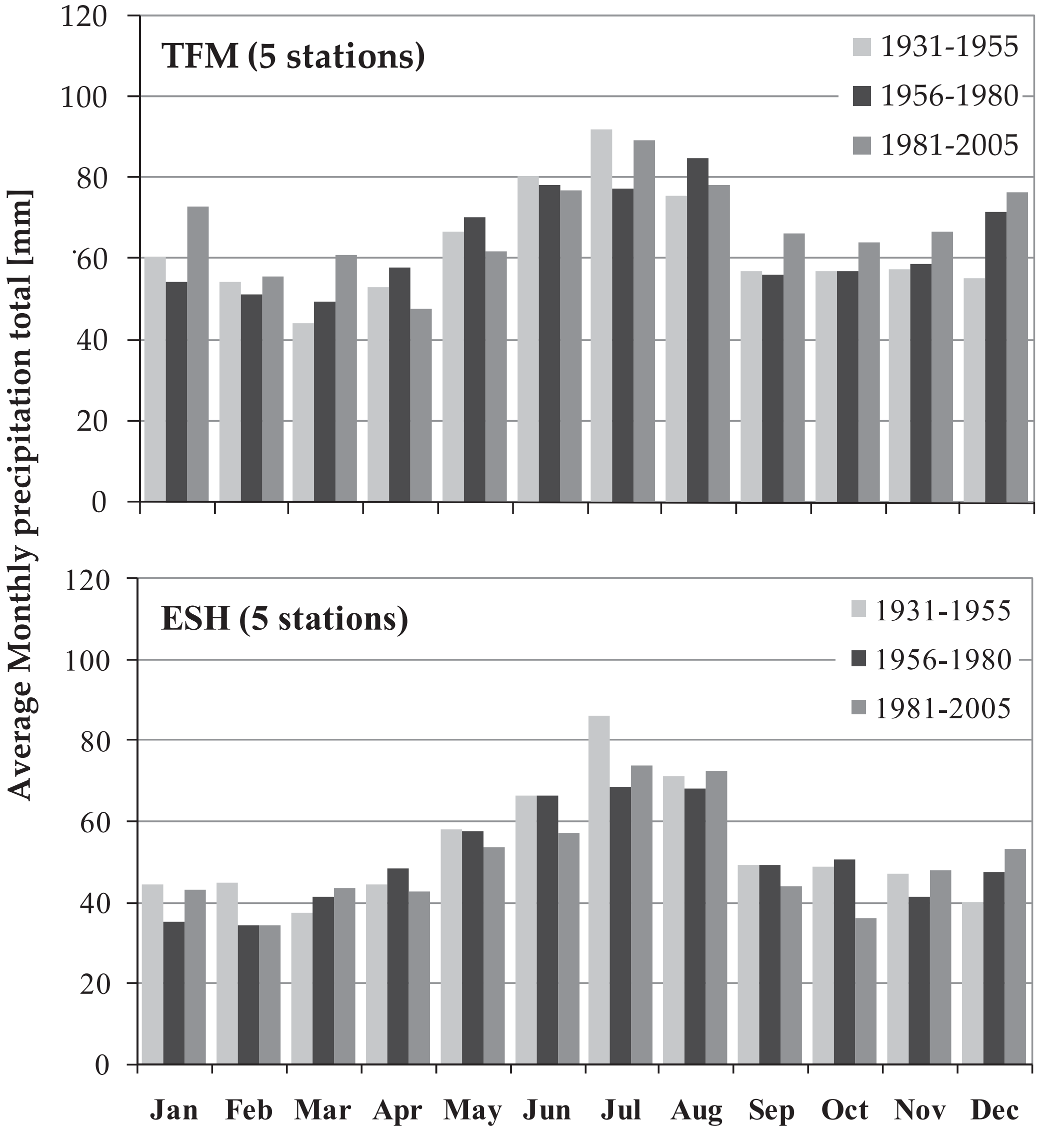


Figure 7.6: Changes in the annual precipitation cycle of the regions TFM (Thuringian-Franconian Mountains) and ESH (Eastern Saxon Hilly Country) for 1931—1955 compared to 1956—1980 and 1981—2005

than the earlier ones, except for region TFM – the only region with distinct precipitation increases in October. Due to higher precipitation increases in December, compared to October, the relative precipitation minimum of the latest period is in October for region TFM, too. Together with the larger winter maximum, the lower spring and autumn minima indicate a larger inter-annual variation in the water resources for most regions. Within 1981—2005, a third precipitation minimum in April and maximum in March was observed in most regions, due to precipitation increases in March and decreases in April. In other regions like the Eastern and Western Saxon Hilly Country (ESH, and WSH), the precipitation totals of March and April were almost equal.

The influence of the number of stations included in the regional averages of monthly precipitation totals for individual periods on precipitation magnitude and trends seems to be quite low (Figure 7.7). This suggests a high similarity of individual station precipitation time series and connected trends within the classified regions. For instance in region ESH (Eastern Saxon Hilly Country) the monthly averages are slightly higher, when using all stations with sufficient data availability for period 1956 to 2005, compared to the averages resulting from those stations that were used for the longer period 1931—2005 with inferior data availability (Figure 7.7). This bias occurs in all months in a similar extent und thus has just a very weak influence on the final trends. It influences absolute rather than relative values. Therefore, no major differences in the statements about changes in the annual precipitation cycle can be made, when using different stations numbers for regional averaging.

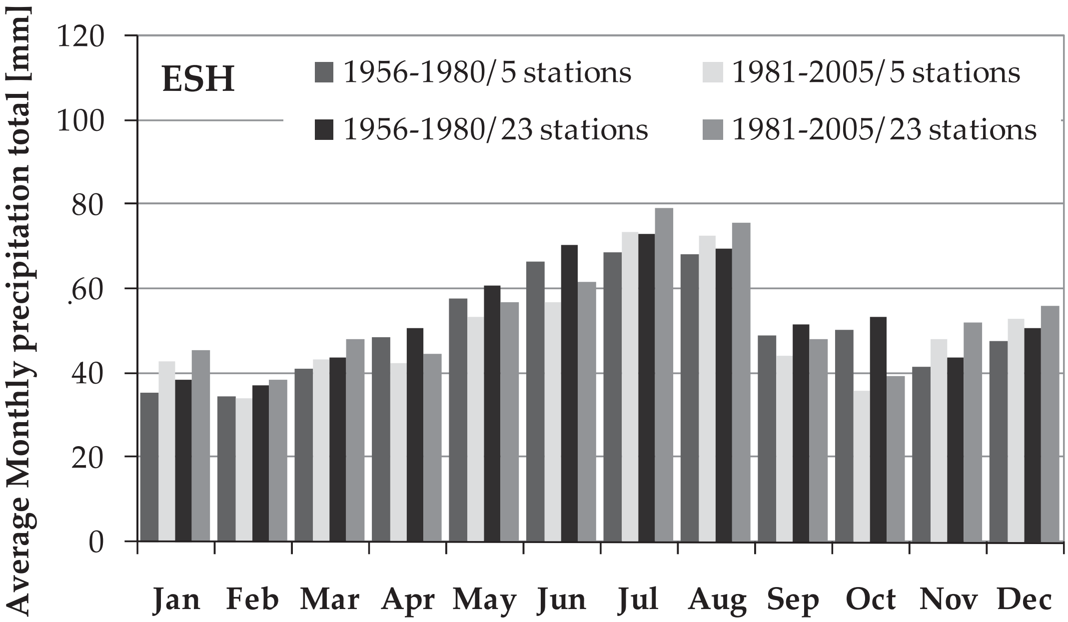


Figure 7.7: Dependence of the regional monthly precipitation averages on the number of stations

7.1.4 Shifts in the Probability Distribution of Monthly Precipitation

Changes in the frequency distribution of monthly rainfall totals became visible next to changes in average precipitation totals (sub-section 7.1.1) and changes in the annual precipitation cycle (sub-section 7.1.3). The regional frequency distributions of monthly precipitation totals have been computed and compared for different periods. First the results for the period with the highest data quality and availability, namely 1951—2000, are presented using the example of the 'Eastern Saxon Hilly Country' (ESH). The frequency distributions are compiled for 25-year periods to compensate for single extreme years. Histograms have been printed separately for the half years (Figure 7.8) as the half

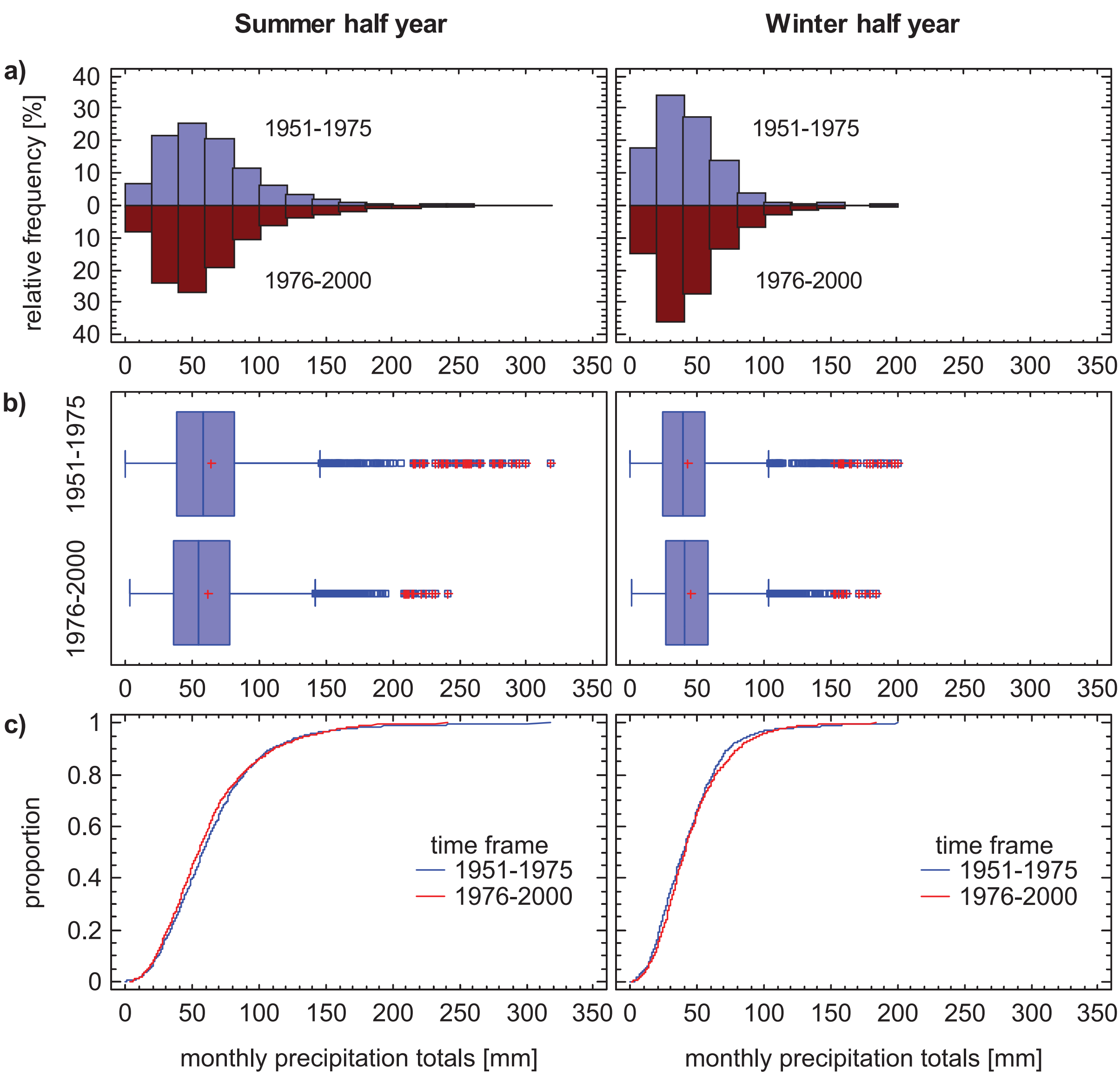


Figure 7.8: Changes in a) the frequency distribution of the monthly precipitation totals, b) the Box- and Whisker plots, and c) the quantile plots of the summer and the winter half year for the Eastern Saxon Hilly Country (ESH) for 1951—1975 compared to 1976—2000

years show opposite trends in precipitation totals. The frequency distribution of the summer half year shifted to smaller classes, when the periods 1951—1975 and 1976—2000 are compared. Small and medium precipitation classes became more frequent during summer and those near or above normal conditions became less frequent. The winter precipitation distribution has shifted in the inverse direction with a decreasing frequency in small precipitation classes and an increase in the frequency of high rainfall classes.

The Box-and-Whisker plots (Figure 7.8b) also show those distribution shifts. The mean, the median, and the 50th percentile of monthly precipitation totals for 1951—1975 within region ESH is higher for the summer half year and lower for the winter half year as compared to 1976—2000. The first period shows noticeably more and larger outliers than 1976—2000, true for both half years. The described changes in mean, median and the distributions themselves are significant for region ESH (Table 7.4).

Table 7.4: Test statistics for the comparison of the monthly rainfall frequency distributions for the half years for two 25-year time intervals (I: 1951—1975 and II: 1976—2000); significant ($\alpha \leq 0.05$) precipitation increases/ decreases are marked by light blue/ orange colour; bold p-values for the KS test indicate highly significant changes in the frequency distribution

Region-No.	Mean [mm] I	Mean [mm] II	p-value (t-test)	Median [mm] I	Median [mm] II	p-value (U-test)	ND	p-value (KS-test)
Summer half year								
TFM	73.5	70.6	0.020	65.8	63.4	0.170	no	0.111
VTB	70.0	66.9	< 0.001	63.0	61.9	0.025	no	0.055
WEG	88.4	84.2	< 0.001	80.0	77.0	0.004	no	**< 0.001**
EEG	80.0	77.4	0.012	71.0	68.9	0.04	no	**0.008**
EGF	71.4	70.2	0.314	64.0	65.0	0.757	no	0.120
WSH	58.4	55.0	< 0.001	52.7	50.2	< 0.001	no	**< 0.001**
ESH	64.1	61.5	0.005	58.0	54.0	< 0.001	no	**< 0.001**
EML	57.4	52.1	< 0.001	51.6	48.0	< 0.001	no	**< 0.001**
LAS	67.0	63.9	< 0.001	59.0	56.0	< 0.001	no	**< 0.001**
Winter half year								
TFM	56.8	67.9	< 0.001	48.4	58.7	< 0.001	no	**< 0.001**
VTB	45.6	49.7	< 0.001	40.8	45.0	< 0.001	no	**< 0.001**
WEG	66.1	67.0	0.194	59.0	58.0	0.099	no	**< 0.001**
EEG	57.8	60.3	0.002	52.0	52.0	-	no	**< 0.001**
EGF	49.3	51.8	0.007	45.0	45.0	-	no	**< 0.001**
WSH	37.5	40.6	< 0.001	34.0	36.6	< 0.001	no	**< 0.001**
ESH	43.3	45.3	0.001	39.0	40.0	< 0.001	no	**< 0.001**
EML	39.3	42.2	< 0.001	36.0	38.5	< 0.001	no	**< 0.001**
LAS	47.3	49.8	< 0.001	42.0	43.2	< 0.001	no	**< 0.001**

ND normal distribution, *KS* Kolmogorov-Smirnov

The other regions behave similar to region ESH with most of them showing different distributions in the two time intervals 1951—1975 and 1976—2000; especially in the winter half year with high significance (Table 7.4). For the summer half year only the changes in mean, median and distribution of the regions TFM and EEG are non-significant, while the Erzgebirge regions (WEG, EEG, and EGF) show non-significant trends during the winter half year with equal medians in regions EEG and EGF and a non-significant increase in mean in region WEG.

The results of the t-test for comparing the means have to be interpreted with care since the condition of normal distribution is not met by the data (Table 7.4). Since the test-results for the significance of the medians are similar to those of the means one can assume that there are significant changes in the mean of the distributions in most regions.

The statistics of the distribution of monthly precipitation totals seems to be more influenced by the number of stations taken into consideration than the annual precipitation cycle described in sub-section 7.1.3. For a considerably smaller station number, the analysis of monthly precipitation distributions was replicated for the periods 1931—1955, 1956—1980 and 1981—2005 (Annex 16; Figure 7.9; Table 7.5). Less statistic significant changes have been found than for 1951 to 2000. This is probably due to the smaller sample size.

Annually, a shift of the regional distributions to medium and high precipitation classes has been noticed from 1931 to 2005 (Annex 16; Figure 7.9). The frequency in the smallest classes decreased. The annual changes in the distribution of monthly precipitation totals, particularly for 1956—1980 in comparison to 1981—2005, are in most regions considerably smaller than the seasonal ones. This is due to opposite precipitation tendencies during the half years.

For the summer half year slight increases in the frequency of the smallest monthly precipitation totals have been observed, but the highest frequencies for period 1931—1955 are reached in lower classes than for the two later time intervals. Altogether the most frequent occupied classes have shifted to higher precipitation totals. For the region WSH the most recent period 1981—2005 is more similar to the eldest one (1931—1955) than to 1956—1980, particularly in the higher precipitation classes (Figure 7.9). But this is not true for all regions (Annex 16). The regional differences in the distribution shifts seem to be higher than the ones in the annual precipitation cycle. Significant changes in the distribution of monthly precipitation totals from period I (1931—1955) to II (1956—1980) have been observed for the regions EEG and WSH (Table 7.5). In contrast, the distributions of 1956—1980 in comparison to 1981—2005 are significantly different for the regions EGF, ESH, EML and LAS.

During the winter half of the year, the shift to higher monthly precipitation totals within 1931—2005 is more pronounced than during summer (Figure 7.9) and the results are more similar to those for period 1951—2000. Increases in the mean and median monthly precipitation totals during winter are only significant

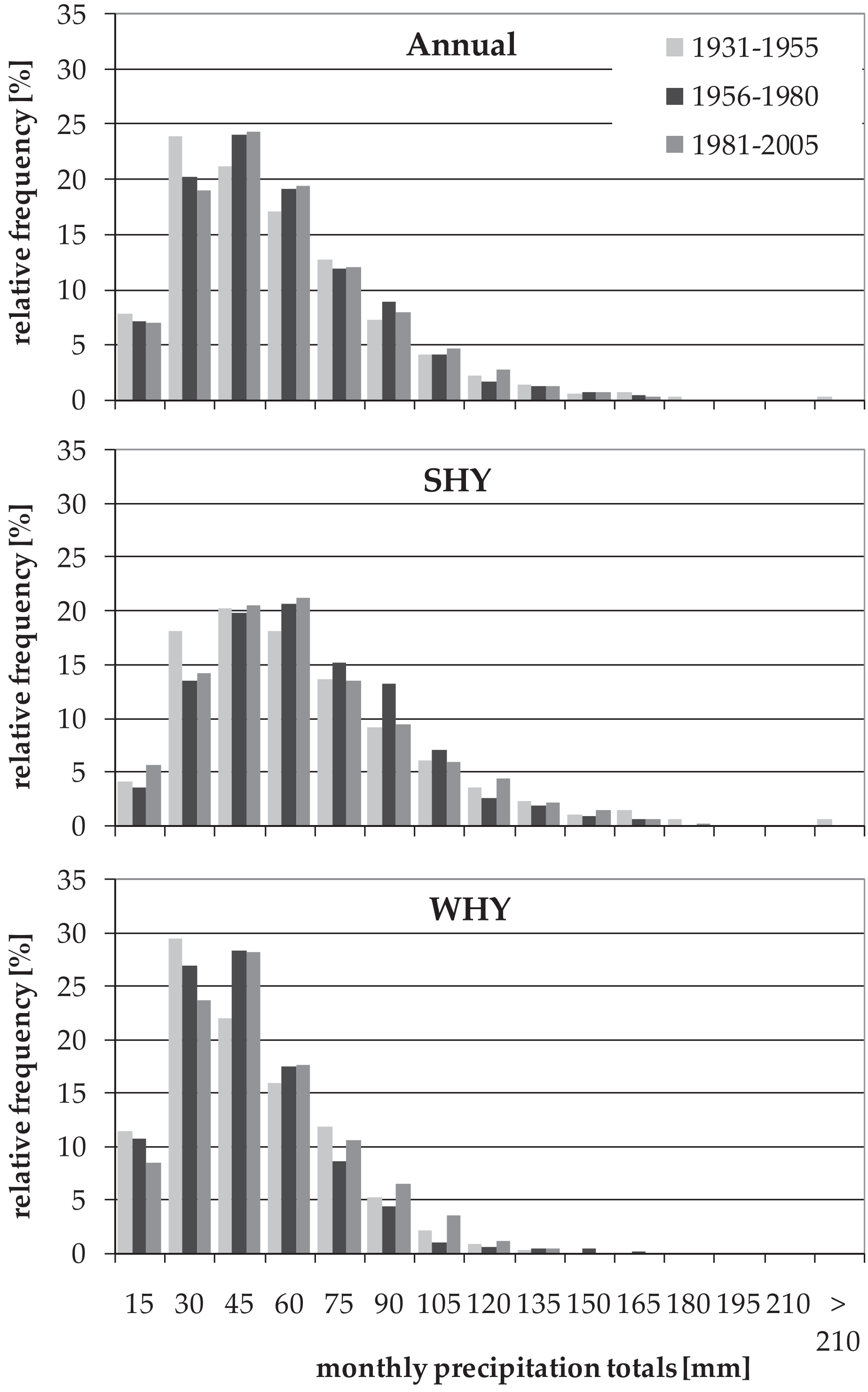


Figure 7.9: Histograms of monthly precipitation totals for the (half)year(s) for 25-year intervals, region WSH (Western Saxon Hilly County, 7 stations); timeframe 1931—2005

between to two most recent periods (Table 7.5). In contrast, the regions WSH, EML and LAS show significant changes in the distribution of monthly precipitation totals between 1931—1955 and 1956—1980. For all regions, except for region ESH, the precipitation distributions of 1956—1980 and 1981—2005 significantly differ from each other.

Analysis of four 25-year intervals within 1906—2005 is possible for a small number of regions (EGF, WSH and LAS), only. For each region four stations were included in the regional averages and distributions. The results are displayed in Table 7.6 for the two half years. During the summer half year significant decreases in mean and median precipitation have been observed in all three regions. Additionally, the highest monthly precipitation totals have been observed in the first half of the study period. Generally, the first period 1905—1930 is most different from the three other ones that form a homogenous group according to the Fisher LSD-test. Thus, significant differences in the distribution

Table 7.5: Test statistics for the comparison of the monthly rainfall frequency distributions of the half years for three 25-year intervals (I: 1931—1955, II: 1956—1980 and III: 1981—2005); significant ($\alpha \leq 0.05$) precipitation increases/ decreases are marked by light blue/ orange colour; bold p-values indicate highly significant changes in the frequency distribution

	Mean			p-value (t-test)		Median			p-value (W-test)			p-value (KS-test)	
	I	II	III	I / II	II / III	I	II	III	I / II	II / III	ND	I / II	II / III
Summer half year													
TFM	71.0	70.8	70.1	0.918	0.712	64.0	64.2	63.9	0.603	0.913	no	0.612	0.624
VTB	65.3	65.9	62.8	0.751	0.042	58.0	60.5	59.7	0.131	0.164	no	0.156	0.170
OEG	83.5	78.4	77.7	0.004	0.676	72.2	71.0	70.0	0.047	0.699	no	**0.021**	0.389
EGF	73.7	71.1	69.4	0.244	0.357	63.0	67.0	62.3	0.607	0.186	no	0.185	**0.050**
WSH	58.9	58.7	57.3	0.886	0.301	51.0	54.2	53.0	0.076	0.086	no	**0.014**	0.079
ESH	62.6	59.8	57.3	0.143	0.172	55.0	55.0	50.9	-	0.045	no	0.238	**0.005**
EML	57.5	56.8	53.1	0.705	0.024	49.7	51.8	49.6	0.426	0.010	no	0.160	**0.011**
LAS	63.9	63.4	60.9	0.681	0.027	57.0	57.0	54.0	-	0.008	no	0.259	**< 0,001**
Winter half year													
TFM	54.9	57.1	66.3	0.255	< 0,001	45.4	49.6	58.4	0.127	< 0,001	no	0.122	**< 0,001**
VTB	45.0	46.8	51.1	0.208	0.002	40.0	41.2	45.6	0.308	< 0,001	no	0.118	**0.003**
OEG	59.9	60.1	65.0	0.876	< 0,001	53.0	54.0	57.0	0.567	< 0,001	no	0.160	**< 0,001**
EGF	48.9	48.2	51.3	0.662	0.041	43.0	43.0	45.0	-	0.017	no	0.487	**0.008**
WSH	40.6	40.4	43.7	0.880	0.002	35.0	37.0	39.2	0.821	< 0,001	no	**0.017**	**0.004**
ESH	43.8	41.8	43.0	0.154	0.362	37.8	37.0	38.5	0.303	0.199	no	0.056	0.282
EML	39.1	40.5	43.9	0.290	0.007	34.0	36.6	39.6	0.129	0.004	no	**< 0,001**	**0.010**
LAS	46.8	46.3	48.7	0.582	0.005	40.0	41.0	42.6	0.883	< 0,001	no	**0.021**	**< 0,001**

ND normal distribution, *KS* Kolmogorov-Smirnov of monthly precipitation totals for the summer half year have been found mainly for the first period in comparison to the other ones. In region LAS, the distribution of the last period significantly differs from all other periods.

Significant increases in mean and median monthly precipitation totals during the winter half year have been observed only in region WSH (Table 7.6). This is also the sole region for which the last period (1981—2005) is significantly different

Table 7.6: Test statistics for the comparison of the monthly rainfall frequency distributions of the half years for the time intervals I (1906—1930), II (1931—1955), III (1956—1980) and IV (1981—2005) for the regions EGF (Erzgebirge Foreland), WSH (Western Saxon Hilly Country) and LAS (Lausitz and Spreewald); significant ($\alpha \leq 0.05$) changes are marked by bold p-values

		Maximum [mm]	Mean [mm]	p-value (F-test)	Homogeneous. groups (Fisher LSD-test)		Median (mm)	p-value (KW-test)	p-value (KS-test)			
									I	II	III	IV
Summer Half Year												
EGF	**I**	291.2	80.4	**<0,001**	x		73.3	**0.001**	-	**0.004**	**0.003**	**<0,001**
	II	364.0	73.8			x	63.5			-	0.347	0.672
	III	261.0	71.3			x	67.8				-	0.131
	IV	229.4	70.1			x	62.6					-
WSH	**I**	261.3	63.6	**0.009**	x		57.0	**0.046**	-	**0.022**	0.056	**0.011**
	II	246.0	59.3			x	51.0			-	0.088	0.363
	III	161.0	58.0			x	55.0				-	0.084
	IV	183.5	56.9			x	52.0					-
LAS	**I**	238.0	67.8	**0.011**	x		58.5	**0.006**	-	0.056	**0.071**	**<0,001**
	II	293.0	63.6		x	x	56.0			-	0.728	**0.045**
	III	212.3	63.6		x	x	57.1				-	**0.032**
	IV	273.1	60.5			x	54.2					-
Winter Half Year												
EGF	**I**	158.0	49.8	0.359	x		43.9	0.261	-	0.727	0.312	0.101
	II	187.0	48.3		x		42.8			-	0.540	**0.032**
	III	189.1	48.5		x		43.0				-	0.128
	IV	161.1	51.0		x		44.3					-
WSH	**I**	173.0	43.0	**0.039**	x		38.0	**0.011**	-	0.251	0.605	**0.018**
	II	132.0	43.1		x		36.9			-	0.077	**0.002**
	III	164.0	42.1		x		39.0				-	**0.026**
	IV	122.1	46.1			x	42.1					-
LAS	**I**	242.0	46.5	0.316	x		42.0	0.200	-	0.054	0.636	0.347
	II	178.0	43.7		x		39.0			-	**0.017**	**0.007**
	III	172.2	45.7		x		41.6				-	0.532
	IV	144.2	46.0		x		41.0					-

from all other periods. Thus, period IV does not belong to the homogenous group that the three other periods form. For the regions EGF and LAS the distribution of period 1981—2005 significantly differs from the one of 1931—1955.

Changes in the distribution of precipitation totals between the periods 1956—1980 and 1981—2005 have also been analysed for individual months (Figure 7.10,

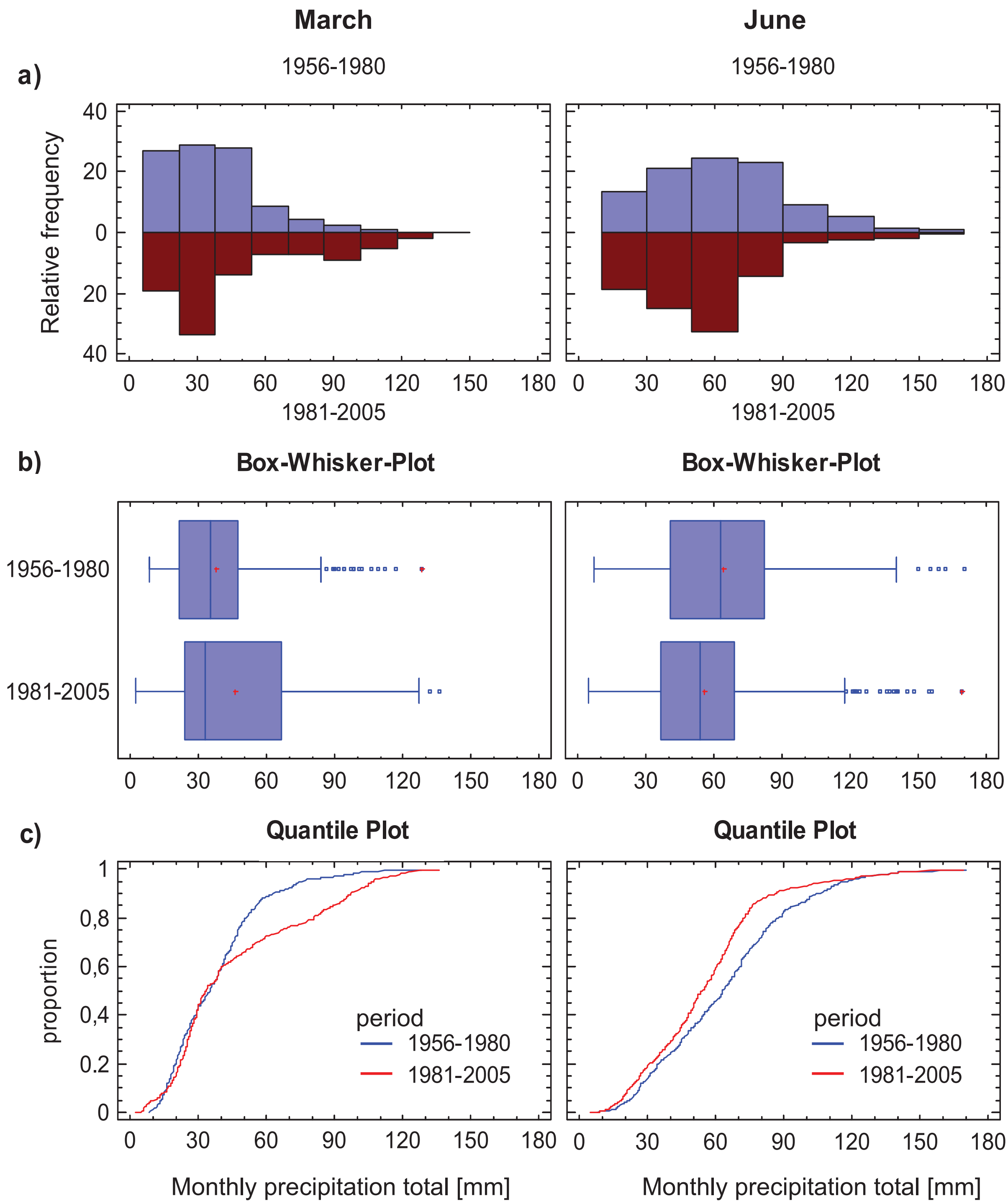


Figure 7.10: Changes in a) the frequency distribution of the monthly precipitation totals, b) the Box- and Whisker plots, and c) the quantile plots of March and June for the Elbe Mulde Lowlands (EML) for 1956—1980 compared to 1981—2005

Annex 18). In all months, the changes in precipitation distribution between the two 25-year intervals are highly significant in most regions. Shifts to lower precipitation totals, characteristic for the summer half year, are illustrated at the example of June for region EML. For the same region the shift to more frequent higher monthly precipitation totals, representative for the winter half year, is illustrated with the example of March in Figure 7.10. This figure also shows that mean and median precipitation might indicate opposite precipitation trends with high significance (Annex 18). This is due to missing normal distribution of monthly precipitation totals and highly significant changes in the shape of the distribution. Such exceptions have been also observed in February in region EML and in March and May in region LAS.

Significant increases in the mean and median monthly precipitation totals from period 1956—1980 to 1981—2005 have been observed in January, March, July, November and December for the majority of regions (Annex 18). In contrast, the months April to June and October are characteristic for significant precipitation decreases. Regionally inconsistent trends in the mean and median of the regional distributions of monthly precipitation totals occurred in August from 1956 to 2005, with significant decreases in the (south)-western regions TFM, VTB, WSH and the eastern region LAS, while the Erzgebirge regions (WEG and EEG) as well as region ESH show significant precipitation increases.

7.1.5 Resume

Changes in annual precipitation averages were spatially and temporally heterogeneous with more frequent positive trends for longer timeframes (1901/1931 to 2006) and approximately equivalent numbers of positive and negative trends for recent periods (1951—2006). A gradient in trend direction and magnitude was noticed, following the prevailing wind direction from West to East. Significant annual precipitation increases were observed in the south-western region TFM, while decreases most frequently occurred in Eastern Saxony (LAS). The annual trends were generally comparatively small due to opposite developments in the half years (Hänsel et al. 2005; Rapp and Schönwiese 1997). April to July most significantly contributed to the precipitation decreases during the SHY that were most pronounced in the north-eastern regions ESH, EML and LAS. Considerable precipitation increases during summer were only observed for August in the Erzgebirge (WEG, EEG and EGF) and region ESH as well as for September in region TFM. The largest precipitation increases during the WHY occurred in March and November as well as in February and December with slightly smaller magnitudes. Significant precipitation decreases during the WHY were calculated for October in all regions, except for region TFM. Spring and autumn trends were less significant than those of summer and winter for most regions, due to opposite monthly trends.

Shifts in the annual precipitation cycle became visible, triggered by opposite monthly trend directions. Matching the regionally quite homogenous monthly trends, the changes in the annual precipitation cycle were very similar for individual regions, with the largest differences for region TFM. The summer precipitation maximum decreased slightly and shifted from early (June, July) to late summer (July, August). The smaller winter precipitation maximum increased and shifted in the opposite direction from late (January, February) to early winter (December). The winter and summer maximum converged, particularly in the region TFM. The autumn precipitation minimum that has earlier been quite evenly distributed from September to November shifted to October and got considerably smaller.

Significant changes occurred not only in precipitation averages, but also in its distribution with higher regional differences than for changes in the annual precipitation cycle. Small and medium monthly precipitation totals became more frequent during the SHY in period 1951—2000, matching decreasing precipitation averages. Opposite shifts were observed in the WHY distribution. In individual months, opposite trends might be indicated by mean and median precipitation values with high significance, due to the non-normal distribution of monthly precipitation data and considerable changes in the shape of the distribution.

Although short-term trends were highly variable in time and space, some trend pattern became visible in the moving 30-year trend analysis, particularly pronounced for monthly trends. For most months and seasons, the trends were of same direction for the majority of stations and trend reversals occured quite simultaneously in different regions, suggesting a high spatial representativeness of trends. Those trend patterns indicate a high influence of large-scale precipitation triggers on precipitation changes. Highly persistent positive 30-year-trends were observed for March, November and December, the months with the most significant long-term trends, while negative trends are of high persistence in May and October. The 30-year trends in August were regionally most heterogeneous, indicating a high influence of small-scale and local precipitation characteristics (convective precipitation) on the trends.

7.2 Changes in Drought Characteristics and Patterns

For the analysis of dry periods, based on daily precipitation data, particularly rigorous criteria for the selection of time series were necessary, as every day with missing precipitation information terminates an existing drought event. Only 105 out of the 130 stations (Figure 7.11) had daily precipitation time series with a manageable amount of gaps that allowed trend analysis for most seasons. Trend analysis was only carried out if ≤10% of the time series elements were missing.

7.2.1 Duration of Dry Periods

Changes in the drought duration were analysed using several meteorological dry period indicators based on daily precipitation data as well as the decile indicator based on three-month precipitation totals. Thus, dry events of different duration are represented by these indicators, from very short but severe

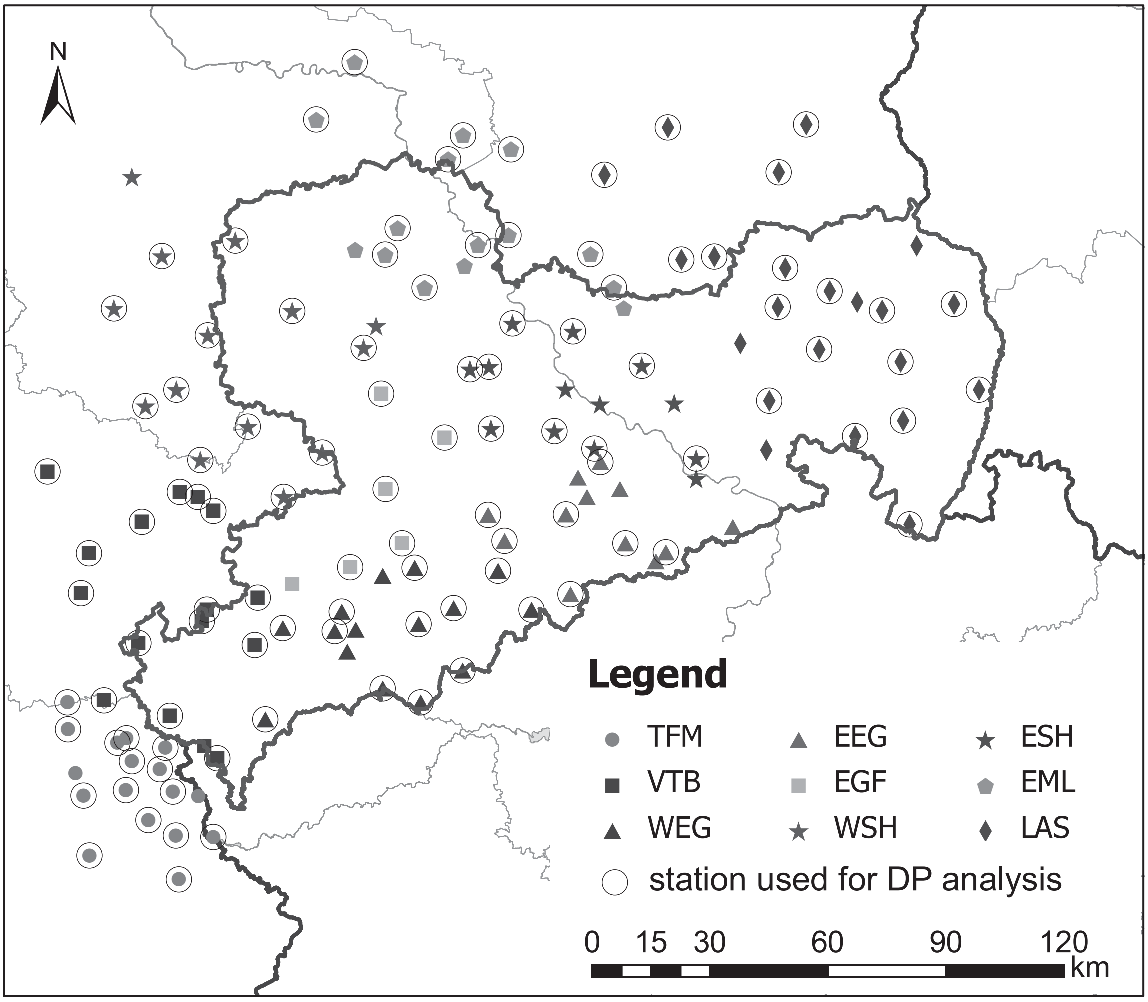
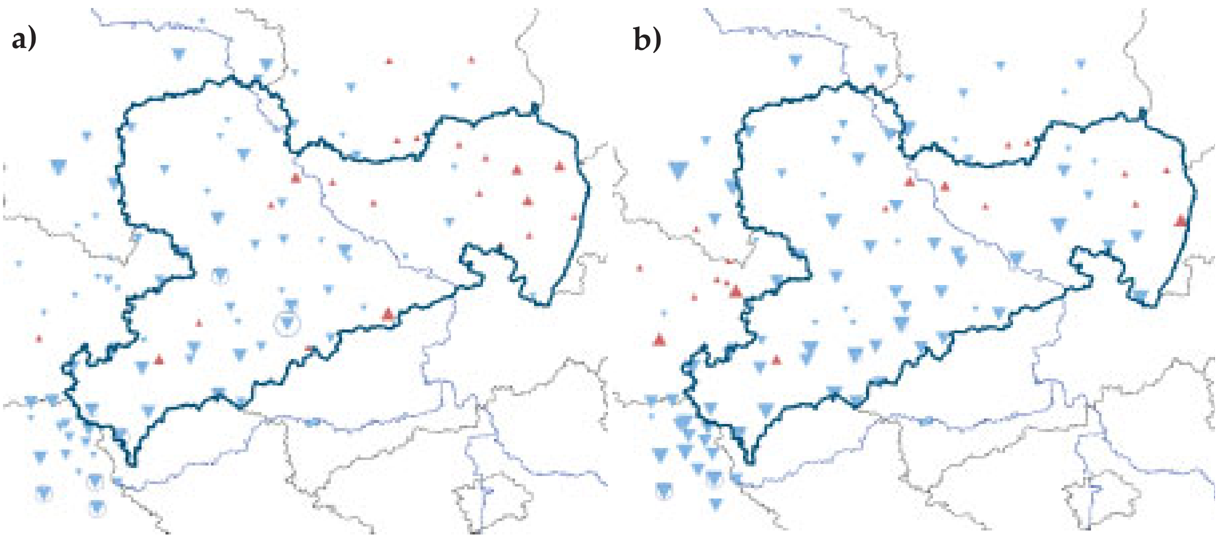


Figure 7.11: Map of all stations with labels for those used for the analysis of dry periods based on daily precipitation data (DP) in individual regions

periods of a few weeks duration to long-term drought conditions lasting several years. Due to the better data availability of monthly precipitation data compared to daily ones, longer timeframes may be analysed for drought indicators based on monthly data. Analysis for daily dry period indicators is done for period 1951—2006 and for monthly indicators additionally for 1901—2006.

Meteorological dry periods (DP): Annually, short term drought conditions, measured by the meteorological dry period concept, have decreased in their average and maximum duration (Figure 7.12, Figure 7.13). Small positive trends have been observed in Eastern Saxony only (mainly region LAS). The maximum dry period duration also increased slightly in the Thuringian Basin west of Saxony.

Significant are about 20% of the negative station trends of average annual dry period duration (Figure 7.15). Those significant trends are mainly found in the south western regions (TFM, VTB and the Erzgebirge). Matching the general precipitation trends, seasonal differences in the dry period trends are visible (Figure 7.14, Figure 7.13). Longer lasting meteorological dry periods occur during summer consistently with decreasing precipitation totals. More than40% of the positive summer half year trends are significant according to the Mann-Kendall trend test (Figure 7.15). The opposite is true for the winter half year, showing distinct declines in dry period duration. The decreases in



Relative linear trends [%]:
magnitude 0.1-5 5.1-10 10.1-25 25.1-50 > 50.1
direction △ positive ▽ negative wetter drier
Mann-Kendall trends:
significance $\alpha = 0.2$ $\alpha = 0.1$ $\alpha = 0.05$ $\alpha = 0.01$ $\alpha < 0.001$

Figure 7.12: Map of the annual linear trends of a) average and b) maximum duration of meteorological dry periods (1951—2000)

the duration of meteorological dry periods are regionally most homogenous in March, April, October and December.

Quite interesting are the high percentages of negative April and October trends that are significant at a comparatively high percentage of stations for April. The distinct precipitation decreases (Figure 7.4) within those months do

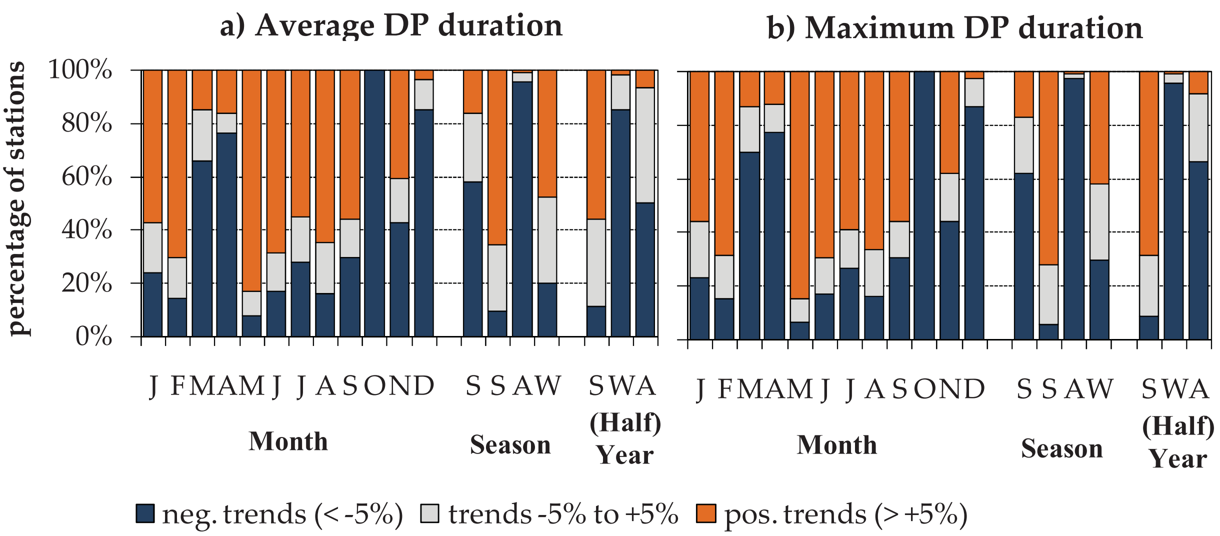


Figure 7.13: Percentage of stations with strong positive and negative linear trends for a) the average and b) the maximum duration of meteorological dry periods for 1951—2000

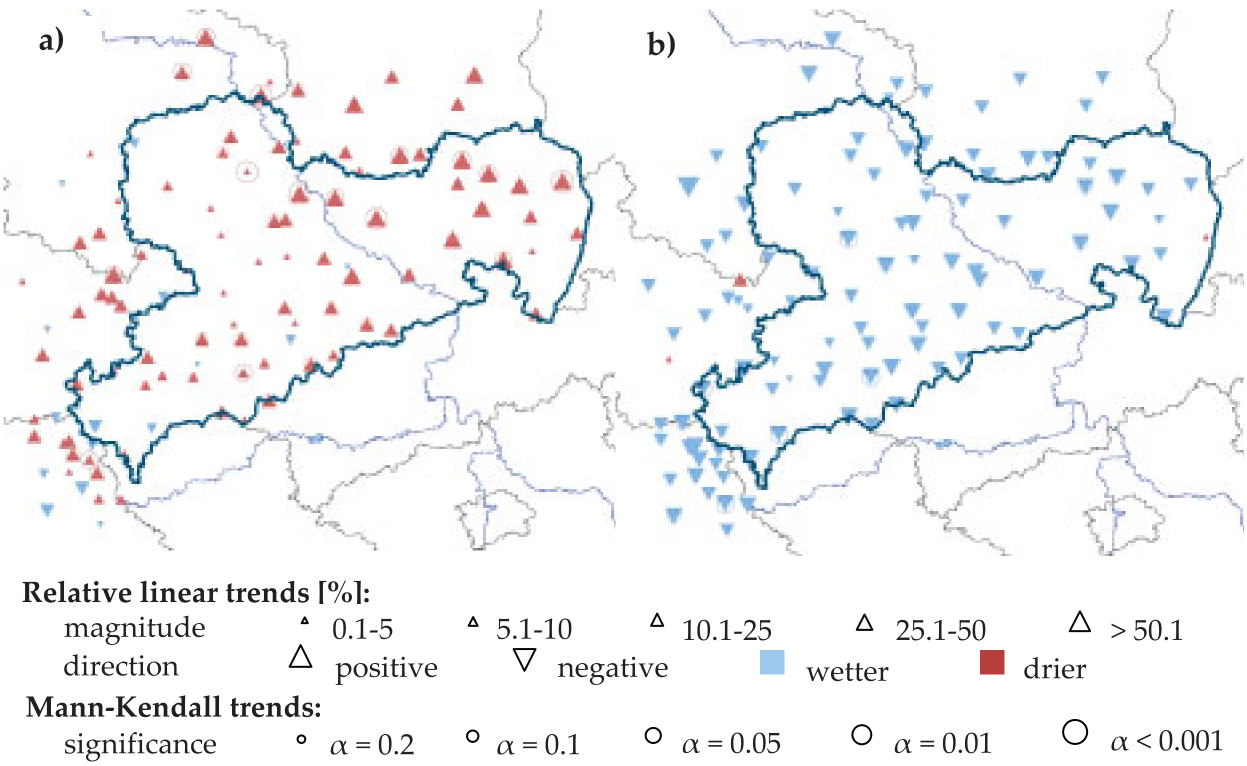


Figure 7.14: Trend map (relative linear trends) of the maximum duration of meteorological dry periods for a) the summer and b) the winter half year (1951—2000)

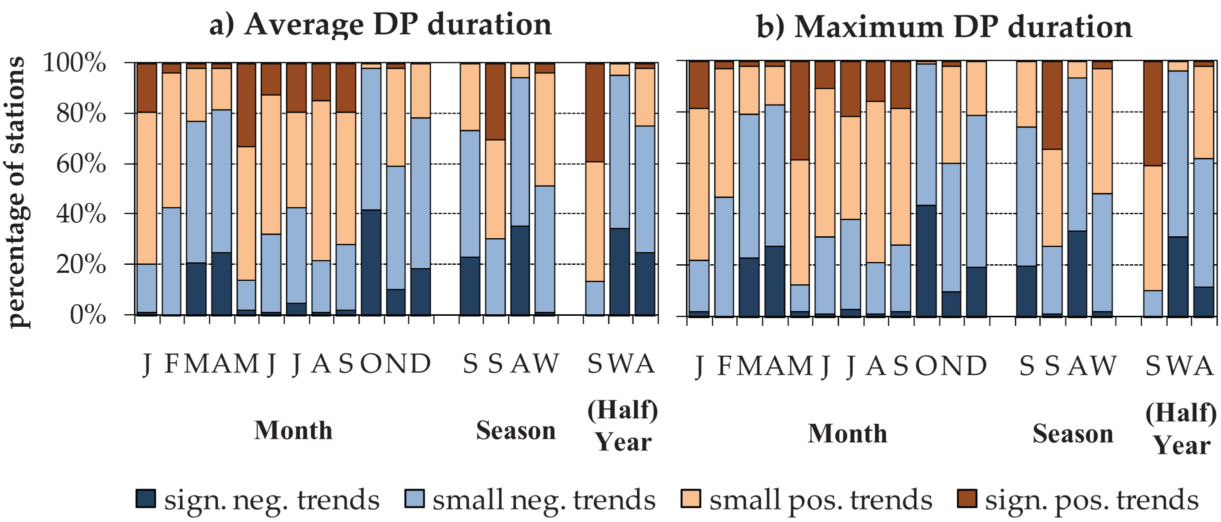


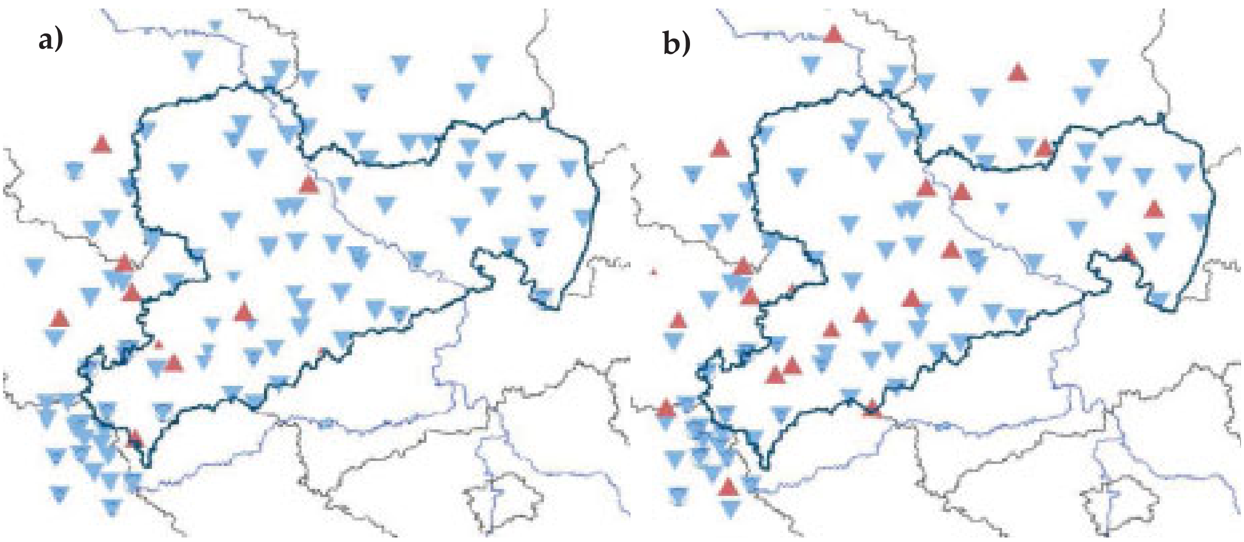
Figure 7.15: Percentage of stations with significant positive and negative trends according to the Mann-Kendall trend test for a) the average and b) the maximum duration of meteorological dry periods for 1951—2000

not seem to further aggravate the drought conditions. On average both months already show the longest meteorological dry periods (Annex 12). Longer meteorological dry periods have been observed at a majority of stations from May to September, but also in January and February the percentage of positive trends is quite high. Significant at a high number of stations are those increases in dry period duration only in May and August. Due to opposite monthly trend directions, the seasonal trends of winter and spring are indifferent in comparison to the summer and autumn trends.

DPST dry periods: Using a variable threshold for the termination of a meteorological dry period that depends on the drought duration (DPST) delivers longer lasting drought events. Due to the longer duration of DPST dry periods (≥ 30 days), only one or no dry event per year occurs in most months and seasons. Therefore, it does not make much sense to average the dry period duration and display the trends of average dry period duration. Figure 7.16 displays the annual trends for the maximum duration of DPST droughts for the absolute threshold of 1 mm and the relative threshold of 75% of daily normal precipitation. For trend analysis, the duration of an individual dry period is assigned to the month of drought termination. Thus, the trends of drought duration for the DPST-indicators have to be interpreted with great care. Although monthly trends of the maximum dry period duration have been calculated (Figure 7.17) their explanatory power is strongly restricted due to the infrequency of such events on a monthly basis. To account for that circumstance and to get information about changes in the extent at which individual months are affected by drought conditions, analysis of dry period days is done in subsection 7.2.2.

Annually, the duration of DPST droughts has declined for period 1951—2000, independently of the chosen threshold (Figure 7.16, Figure 7.17a). Those decreases are significant for about 20% of the stations (Figure 7.17b). Stations with significant negative trends of maximum DPST duration are frequently situated in the Southwest of the study area (regions TFM and VTB).

The differences in the trend patterns of the half year trends are much less pronounced than for meteorological dry periods (Annex 21). For both half years more than 50% of the stations show negative trends of maximum DPST dry period duration, true for both thresholds. Nevertheless, positive trends have been observed at more stations during the winter than compared to the summer half year, particularly in the Northwest of the study area (regions WSH and EML). The negative winter half year trends are most pronounced in the mountainous regions (TFM, WEG and EEG) for the absolute threshold (DPST-1mm). DPST dry periods terminated during the summer half year have decreased in their duration at most stations. A cluster of positive summer trends was observed in the mountainous regions (WEG and EEG) in the south of the study area for the absolute threshold (DPST-1mm) and in central Saxony (EGF, EEG) for the relative threshold (DPST-75%).



Relative linear trends [%]:

magnitude △ 0.1-5 △ 5.1-10 △ 10.1-25 △ 25.1-50 △ > 50.1

direction △ positive ▽ negative ■ wetter ■ drier

Mann-Kendall trends:

significance ○ $\alpha = 0.2$ ○ $\alpha = 0.1$ ○ $\alpha = 0.05$ ○ $\alpha = 0.01$ ○ $\alpha < 0.001$

Figure 7.16: Map of the annual trends (relative linear trends) of the maximum duration of dry periods with an increasing threshold of a) 1 mm (DPST-1mm) and b) 75% of daily normal precipitation (DPST-75%) per continuing dry period day for 1951—2000

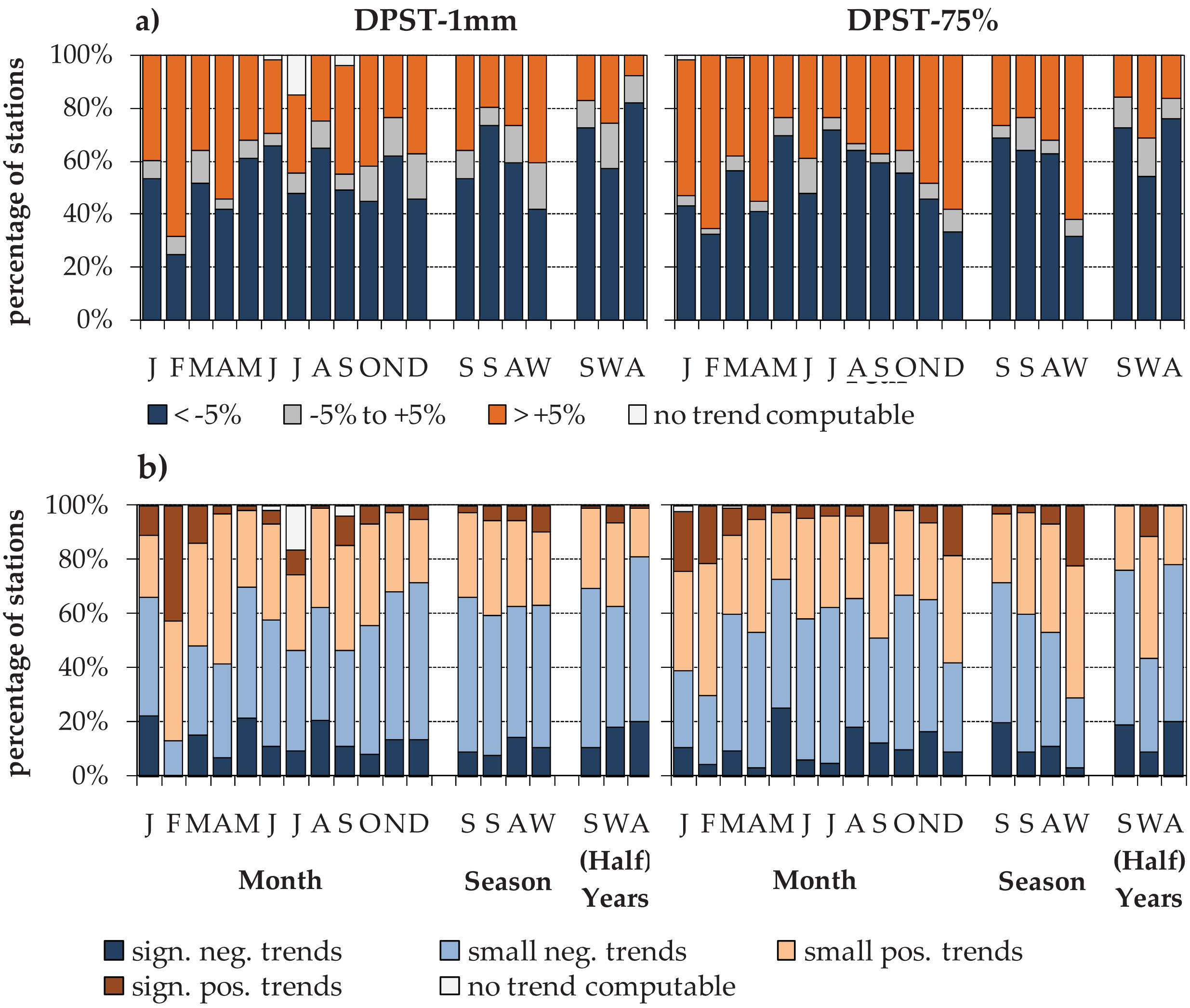


Figure 7.17: Percentage of stations with a) strong positive and negative linear trends and b) significant positive and negative trends according to the Mann-Kendall trend test for the maximum duration of dry periods with an increasing threshold of 1 mm (DPST-1mm; left frame) and 75% of daily normal precipitation (DPST-75%; right frame) per continuing dry period day for 1951—2000

For the winter season, the percentage of positive trends is even higher than for the winter half year, in particular for the relative threshold of 75% of daily normal precipitation (Figure 7.17a). The duration of dry periods that end from December to February has increased at a high percentage of stations, when using the relative 75%-threshold. Significant positive trends for those months show about 20% of the stations (Figure 7.17b).

Decile dry periods: Long-term drought conditions of at least three month duration are measured by the decile indicator. Similar to the longer meteorological dry periods represented by the DPST-indicators, the average decile drought duration has slightly decreased in most regions between 1951 to 2000, apart from region LAS showing a distinct increase (Figure 7.18). In contrast, an increase in the average duration of decile droughts from the first to the second part of the 20th century has been observed over the whole study area (Figure 7.18). Nevertheless, some opposed developments occurred regionally. Whilst in region (TFM) the longest average drought duration has been observed for the first period (1901—1950 and 1926—1950, respectively), the average dry period duration is shorter for the first time slice than for later ones in all other regions.

Changes in the maximum station-based decile drought duration within the nine regions are spatially much more heterogeneous than the average changes (Figure 7.19). Cumulated over all stations, the maximum duration of decile droughts increased between 1901 and 2000 matching the increase in mean duration. Only in one region, namely EEG, the longest decile dry period has been

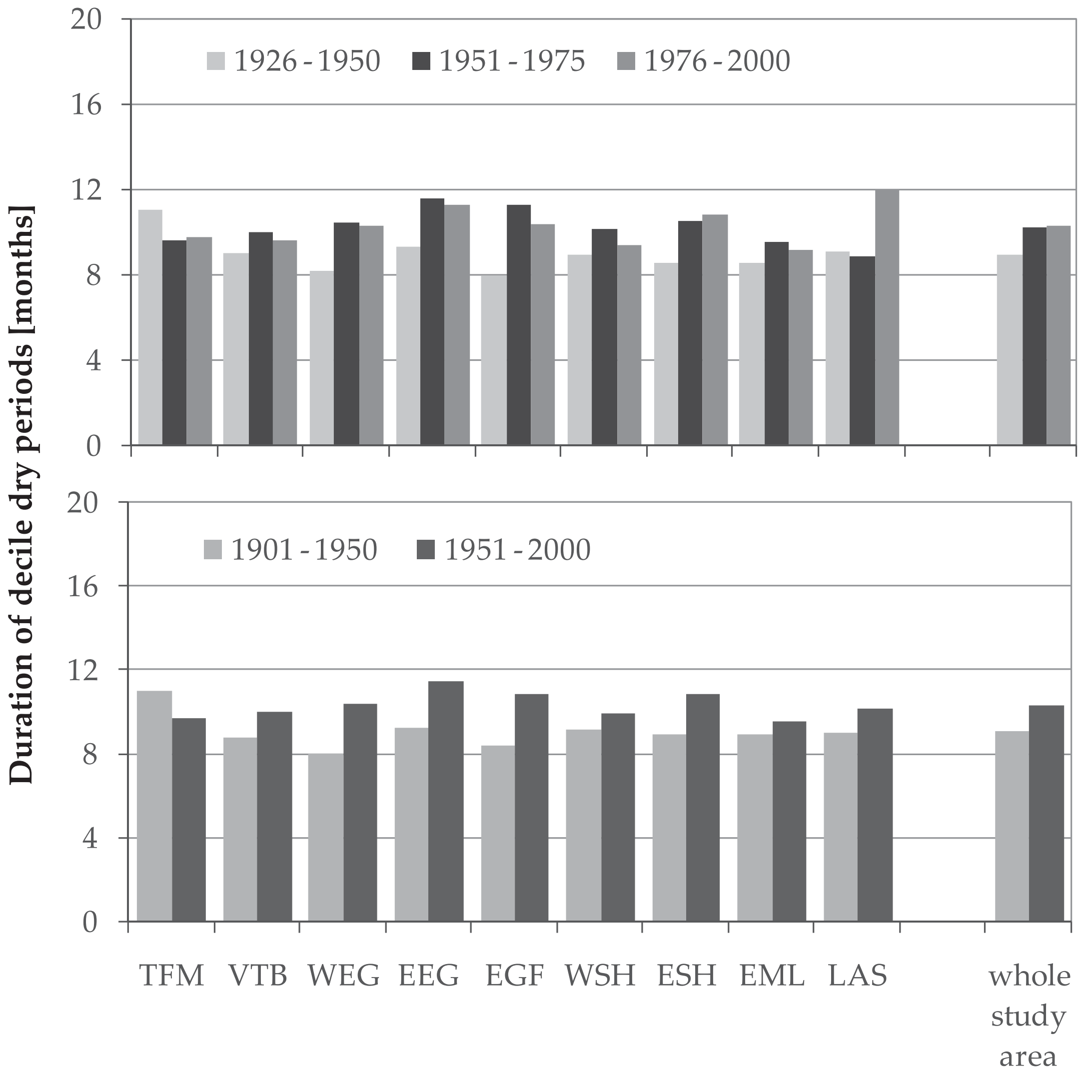


Figure 7.18: Changes in the mean duration of decile dry periods in the nine regions (130 stations) for 25- and 50-year intervals, timeframe: 1901—2000

observed in 1926—1950. In the mountainous regions (VTB, WEG, EEG, and EGF), except for region TFM, the longest decile drought in 1976—2000 has been shorter than the one in 1951—1975.

Changes in the duration of drought events might also be observed by analysing the frequency distribution of drought durations of different time intervals. Despite quite heterogeneous results for 25-year-intervalls, a general shift of thedistribution to higher drought durations from 1926—1950 to 1976—2000 is visible (Figure 7.20). This shift is more clearly visible for 50-year-intervalls. The frequency of short decile droughts (< 11 months) decreased, while long decile droughts (> 16 months) occur more frequent.

Within the regions, similar shifts in the distribution of decile drought duration have been observed (Annex 19). Matching the regional trends of average decile

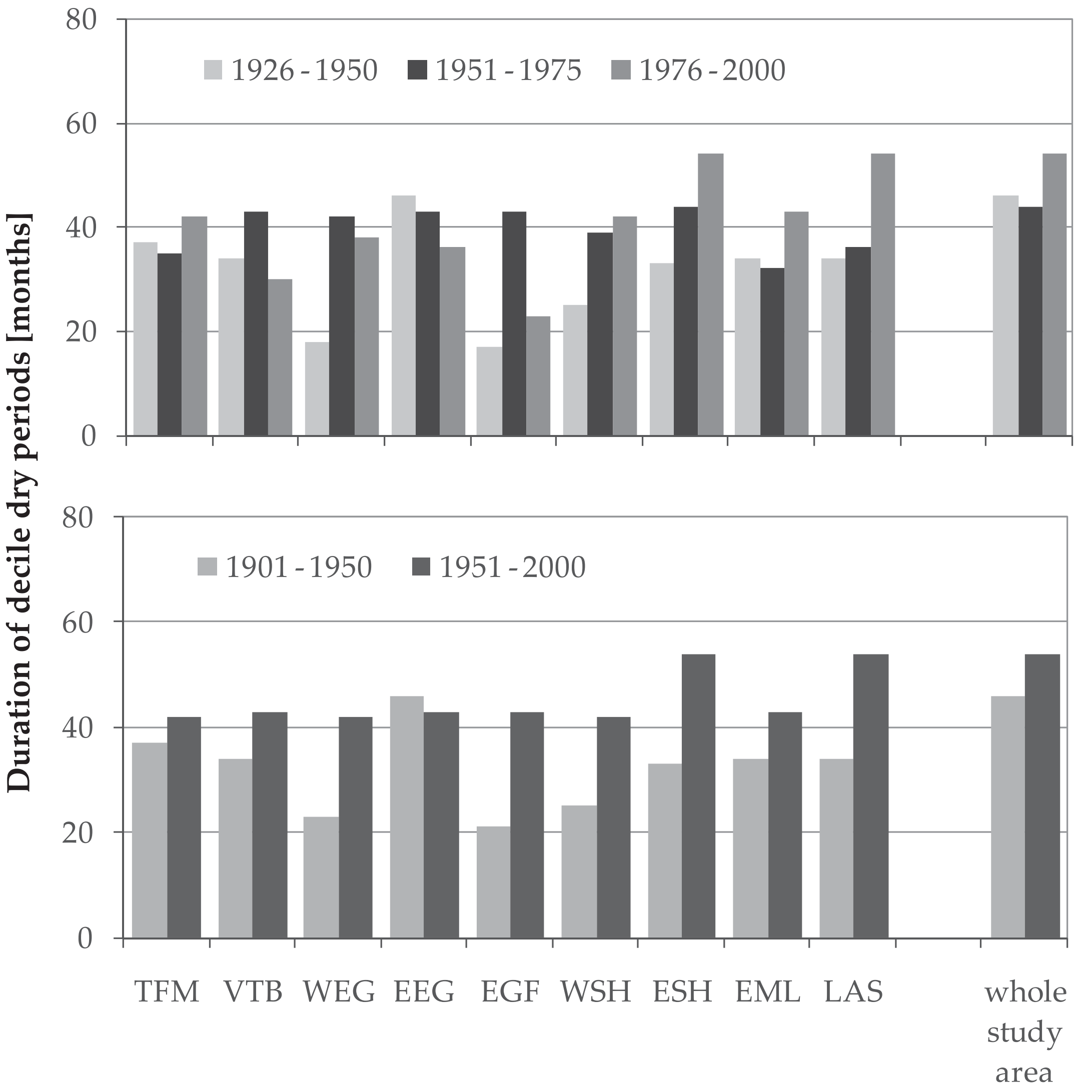


Figure 7.19: Changes in the maximum duration of decile dry periods in the nine regions (130 stations) for 25- and 50-year intervals, timeframe: 1901—2000

dry period duration, the changes in the histogram of region TFM are most different from the other regions. Within this region, short decile droughts (< 6 months) became considerably more frequent, whereas the frequency of events of medium duration (6 to 14 months) decreased. The histograms of the other regions look more similar to each other with the highest frequency of decile droughts lasting 6 to 8 months, true for both periods (1901—1950 and 1951—2000). All regions, except for region EML, show a decrease in the frequency of this duration class. The frequency of long decile droughts of at least 15 months duration increased in most regions (particularly in regions VTB, WEG, EEG, EGF and ESH)

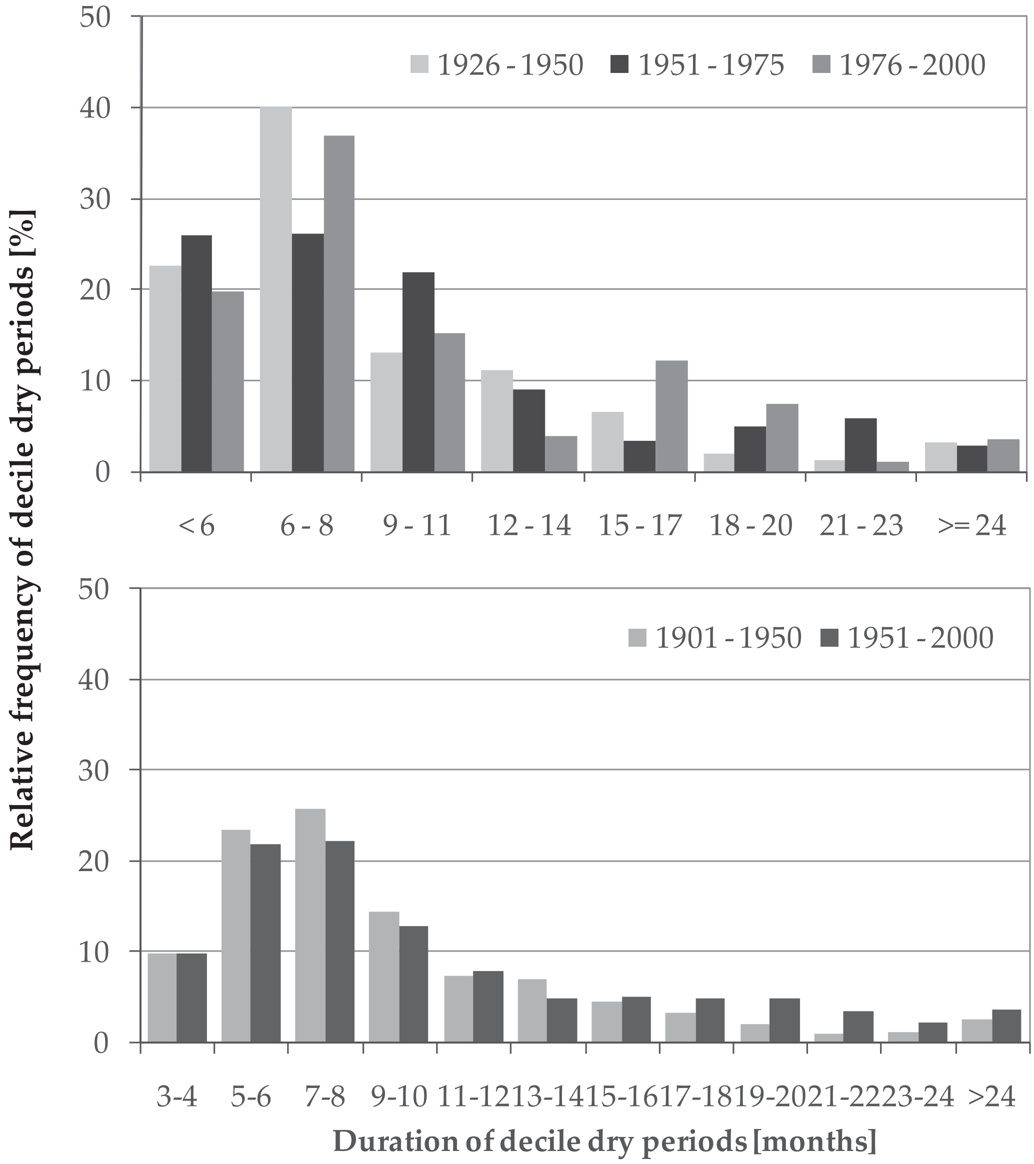


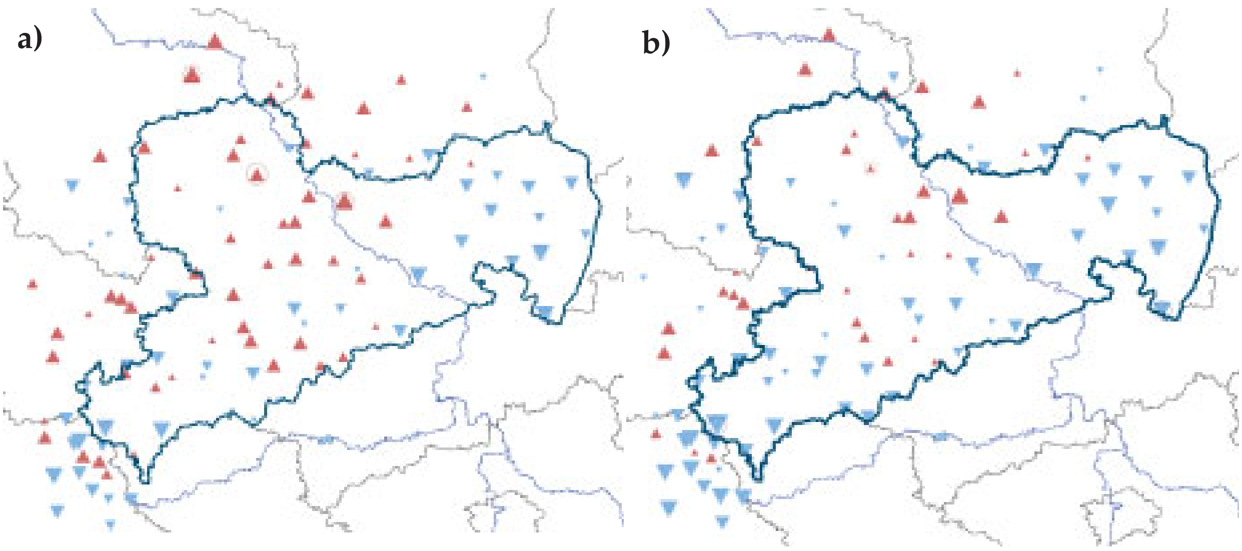
Figure 7.20: Shifts in the histograms of decile drought duration in the nine regions (130 stations) for 25- and 50-year intervals, timeframe: 1900—2000

7.2.2 Frequency of Dry Periods

Changes in the frequency of dry periods are analysed for the same indicators and periods as described in sub-section 7.2.1 for dry period duration.

Meteorological dry periods: Short drought events, measured by the meteorological dry period indicator, show indifferent annual trends for dry period frequency from 1951 to 2000 (Figure 7.21a, Figure 7.22a). North of an imaginary border from southwest to northeast predominantly positive trends occur (mainly regions WSH, ESH and EML as well as the Thuringian Basin part of region VTB), while south of this border negative trends predominate (regions TFM, WEG, EEG and LAS).

Similar annual trend pattern are found for the frequency of days belonging to meteorological dry periods, although less positive trends than for the dry period frequency have been observed (Figure 7.21b, Figure 7.22a). Opposite trend developments of meteorological dry period (day) frequency occur during the half years (Figure 7.23). Matching the general precipitation decreases during summer the frequency of short meteorological drought events as well as the frequency of days belonging to such events increased during the summer half year, while decreases were observed for the winter half year.



Relative linear trends [%]:

magnitude	0.1-5	5.1-10	10.1-25	25.1-50	> 50.1
direction	positive	negative	wetter	drier	

Mann-Kendall trends:

significance	$\alpha = 0.2$	$\alpha = 0.1$	$\alpha = 0.05$	$\alpha = 0.01$	$\alpha < 0.001$

Figure 7.21: Trend map (relative linear trends) of the annual frequency of a) meteorological dry periods and b) dry period days for 1951—2000

The summerly increase in dry period frequency is most pronounced in May and August (Figure 7.22a). A high percentage of those monthly trends is significant according to the Mann-Kendall trend test (Figure 7.22b). Significant summer half year trends (Figure 7.23) are mainly found in the western regions VTB and WSH, but also in Central Saxony (ESH). In contrast, the predominantly positive January trends are not statistically significant. The observed decreases during the winter half year are most pronounced in March, November and December. Less of those negative monthly trends are statistically significant than of the positive May and August trends. April shows the highest percentage of negative station trends. Likewise, the frequency of significant negative trends is highest in April with about 25% of all station trends.

Additionally, to the frequency of meteorological dry periods, the frequency of days belonging to meteorological dry periods is analysed for months and seasons (Figure 7.22). This approach accounts for the circumstance that each

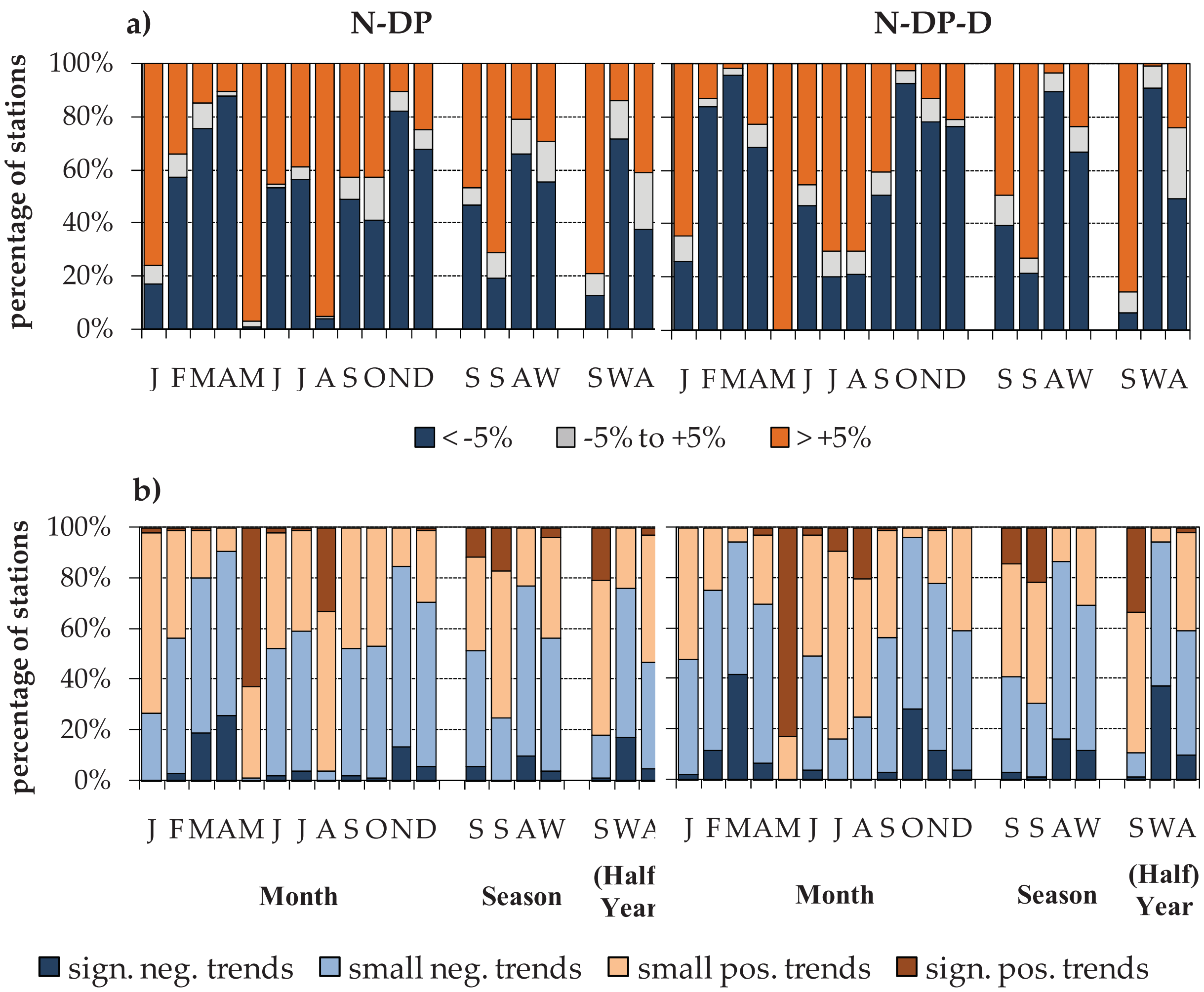


Figure 7.22: Percentage of a) positive and negative relative linear trends and b) their significance according to the Mann-Kendall trend test for the frequency of meteorological dry periods (N-DP) and the frequency of days belonging to meteorological dry periods (N-DP-D) for 1951—2000

meteorological dry period is assigned to the months of its termination. Therefore, the trend results of the dry period frequency are biased to the months of dry period termination. Months with less dry periods might very well be more often affected by drought conditions, if dry periods more frequently end in the following month. This seems to be the case for July (Figure 7.22). Slightly more stations show negative than positive July trends for dry period frequency, while dry period days increased at the majority of stations. Correspondingly, the percentage of stations with positive August trends is higher for the frequency of dry periods than the one of days belonging to dry period. The opposite is the case for October, showing higher percentages of negative trends

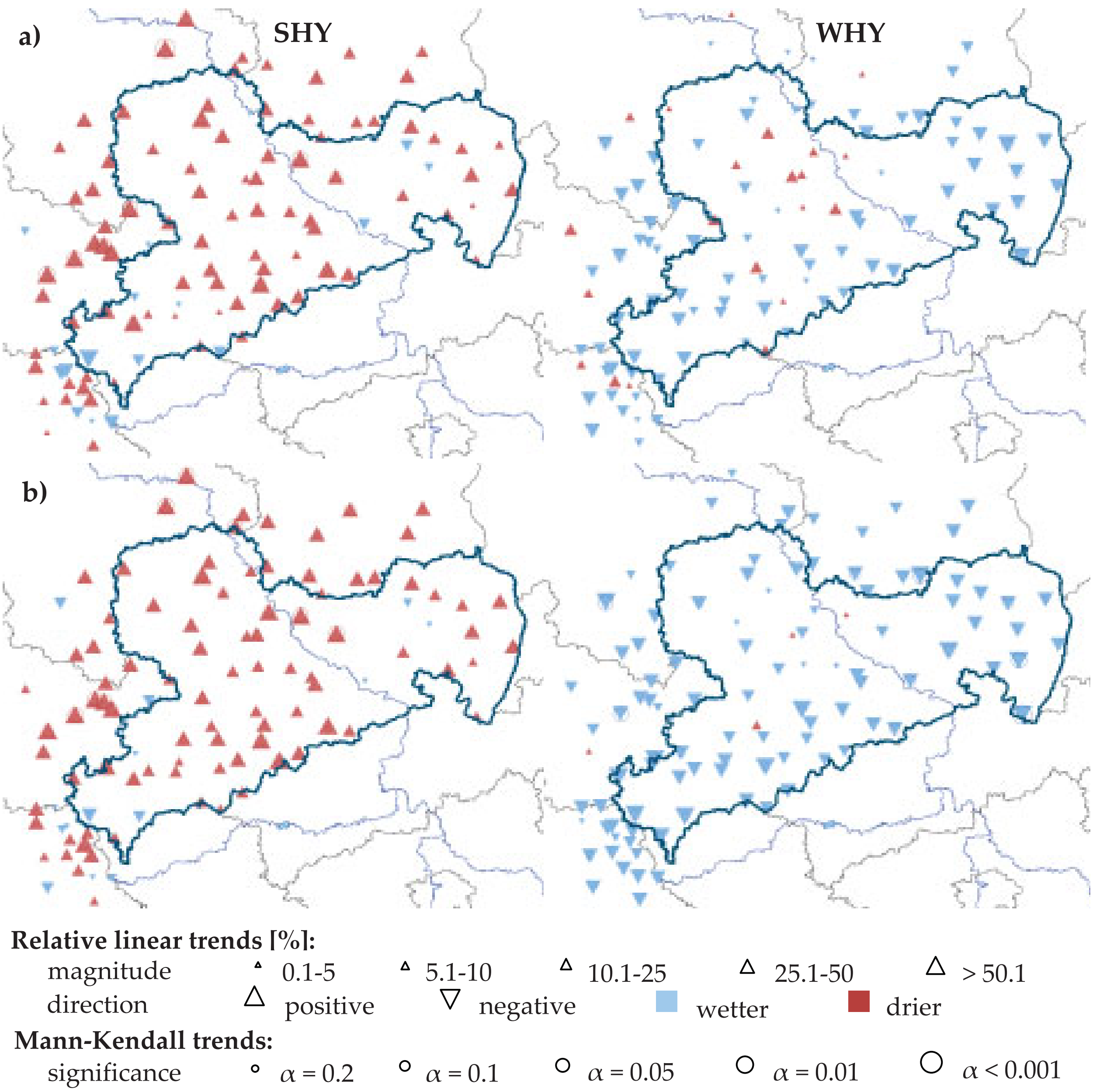


Figure 7.23: Trend map of a) the frequency of meteorological dry periods and b) the frequency of dry period days for the summer (SHY, left) and the winter half year (WHY, right) for 1951—2000

for dry period days than for dry periods themselves. According to the days assigned to meteorological dry periods, October and March became regionally most homogenously less drought affected from 1951 to 2000. For those months, the highest percentage of statistically significant negative station trends has been observed additionally (Figure 7.22). May seems to be the month that became spatially most homogenously more drought affected; more than 80% of the station trends of dry period day frequency are statistically significant according to the Mann-Kendall trend test.

The annual frequency of meteorological dry periods lasting at least 14 or 21 days, respectively, has decreased at the majority of stations, just as the number of days belonging to such dry periods has (Figure 7.24a). Most pronounced are those decreases in autumn and the winter half year. Particularly for the days

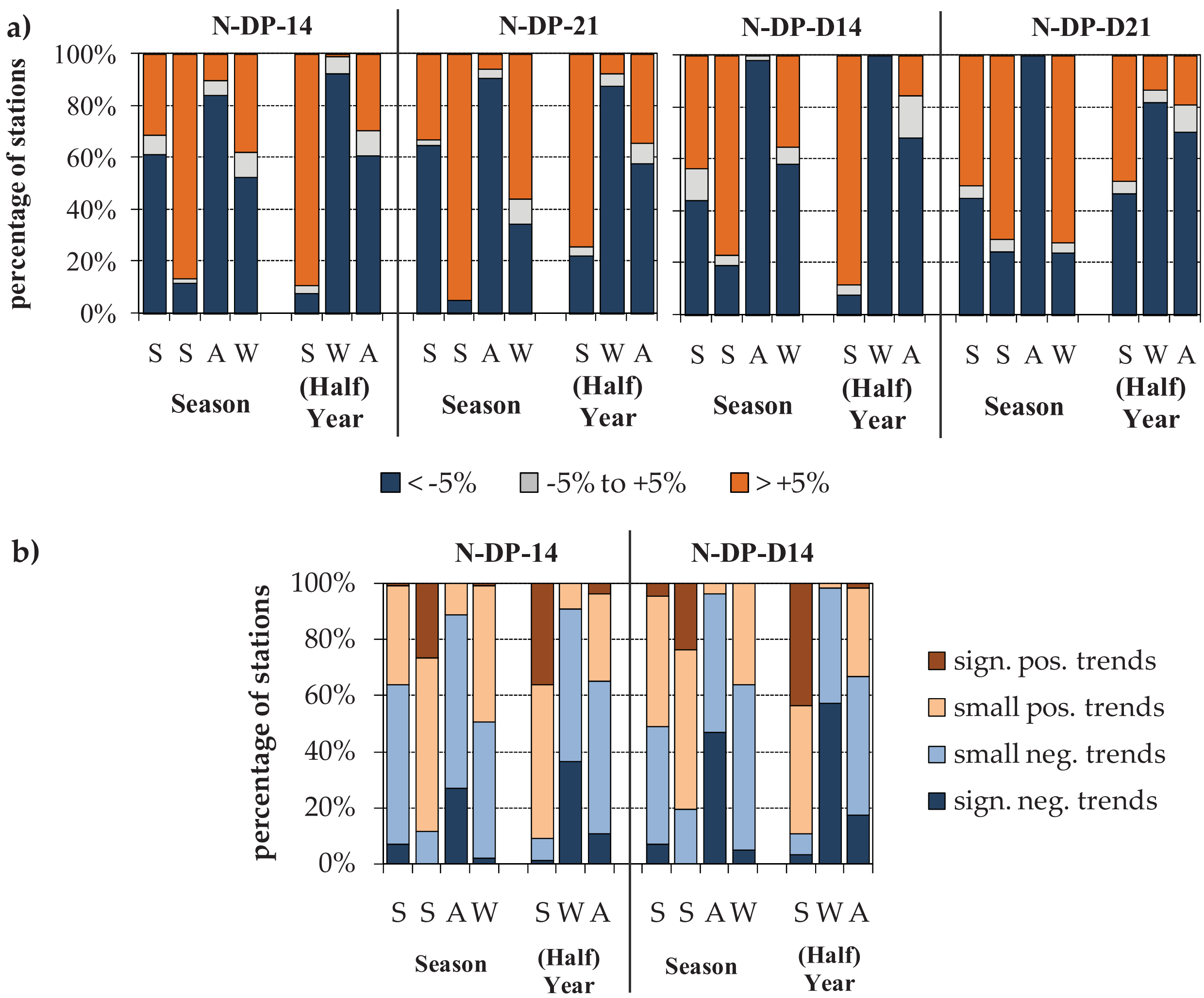


Figure 7.24: Percentage of a) positive and negative relative linear trends and b) their significance according to the Mann-Kendall trend test of the frequency of long meteorological dry periods (N-DP-14 and N-DP-21) as well as the frequency of days belonging to long meteorological dry periods (N-DP-D14 and N-DP-D21) for dry period durations of at least 14/ 21 days for 1951—2000

belonging to dry periods lasting at least 14 days, a high percentage of trends are statistically significant for those seasons (Figure 7.24b).

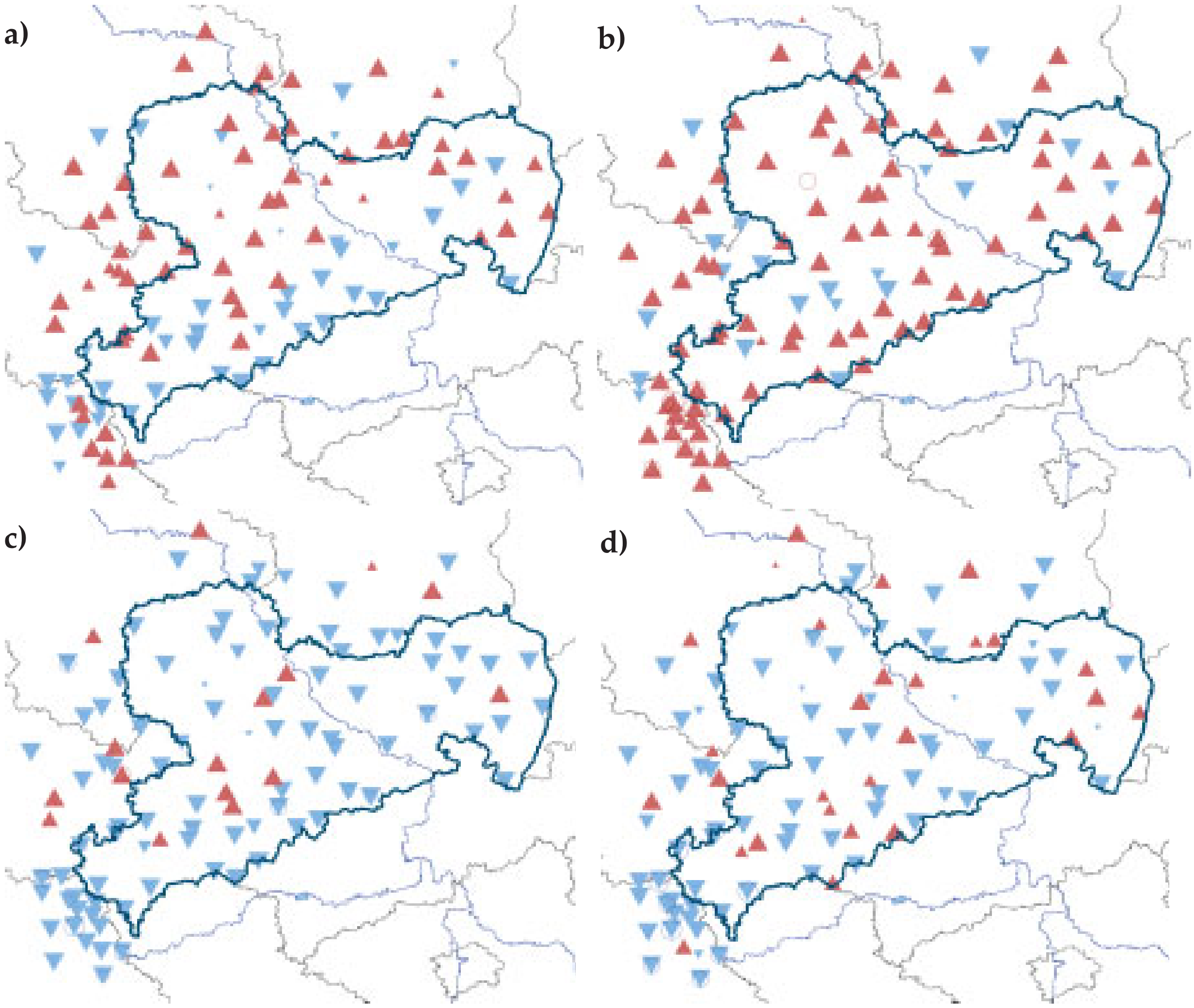
During the summer season and half year the frequency of long (≥ 14/ 21 days) dry periods has increased at a high percentage of stations. Significant Mann-Kendall trends have been calculated for 20% to 40% of the stations (Figure 7.24). For dry periods lasting ≥ 21 days, those results of dry period frequency trend analysis are not completely confirmed by the dry period day trends.

Less stations show positive dry period day trends for the summer season and half year than compared to the trends of dry period frequency. Mann-Kendall trends were not calculated for meteorological dry periods of at least 21 days duration, as those events occur too rarely. Likewise, no monthly trend analysis of long dry periods was done due to their rarity.

DPST-droughts: Longer dry periods measured by the DPST concept have increased in their annual frequency during 1951—2000 (Figure 7.25 a) and b)). Particularly for the relative threshold of 75% of daily precipitation those increases are regionally quite homogenous. In contrast, predominantly negative trends are observed in the mountainous regions (TFM, VTB, WEG and EEG) for the absolute threshold of 1 mm. Therewith, the regional trend patterns of DPST-1mm dry period frequency are similar to those of meteorological dry period frequency (Figure 7.21). Both concepts are based on absolute threshold, hence the regionally opposite trend directions are probably due to the gradient in total precipitation from the lowlands to the low mountain ranges.

Although the annual frequency of DPST droughts has increased in many regions, those regions do not seem to be more frequently and seriously affected by drought conditions, as the frequency of days belonging to a DPST has decreased at the majority of stations for both thresholds (Figure 7.25 c) and d)). The opposite trend information, derived from the frequency of DPST events and days assigned to such periods, indicates that dry periods are more often interrupted by heavy precipitation events and periods in recent times. This assumption is confirmed by the trend results of DPST duration, showing an annual decrease in maximum DPST duration, independently of the chosen threshold.

The half year trends of DPST drought frequency are not as regionally homogenous as those of meteorological dry period frequency (Annex 21). A high percentage of positive trends are calculated for both half years and thresholds (Figure 7.26a). For the absolute threshold of 1 mm, the percentage of positive and negative trends, respectively, is almost equal within the half years. Nevertheless, there are some differences in the regional trend patterns of the half years (Annex 21). During the summer half year, DPST-1mm frequency increased mainly in the North-eastern regions EML, ESH and LAS, whereas during the winter half year, positive trends predominate in the western parts of the study area (TFM, VTB, WSH and EML). For the relative threshold of 75% of daily normal precipitation, the percentage of positive trends is higher the winter as compared to the summer half year (Figure 7.26a). The few negative half year trends are not concentrated in individual regions but are quite



Relative linear trends [%]:

magnitude △ 0.1-5 △ 5.1-10 △ 10.1-25 △ 25.1-50 △ > 50.1

direction △ positive ▽ negative ■ wetter ■ drier

Mann-Kendall trends:

significance ○ $\alpha = 0.2$ ○ $\alpha = 0.1$ ○ $\alpha = 0.05$ ○ $\alpha = 0.01$ ○ $\alpha < 0.001$

Figure 7.25: Map of the annual linear trends of a) the frequency of dry periods with an increasing threshold of a) 1 mm (N-DPST-1mm) and b) 75% of daily normal precipitation (N-DPST-75%) per continuing dry period day as well as the frequency of days belonging to such dry periods with an increasing threshold of c) 1 mm (N-DPST-1mm-D) and d) 75% of daily normal precipitation (N-DPST-75%-D) for 1951—2000

equally distributed over the study area (Annex 21). At about 30% of all stations, the increases in DPST frequency are statistically significant according to the Mann-Kendall trend test (Figure 7.26b).

When looking at the frequency of days belonging to DPST dry periods, the half year trend pattern are more similar to those of meteorological dry period frequency than the trends of DPST frequency, described in the previous paragraph (Annex 21). Compared to the summer half year, the winter half year became much less drought affected, with a high percentage of significant negative trends (Figure 7.27). Although the frequency of DPST days has decreased at more than 50% of the stations during the summer half year, too, there are far more positive summer half year trends as compared to the winter half year.

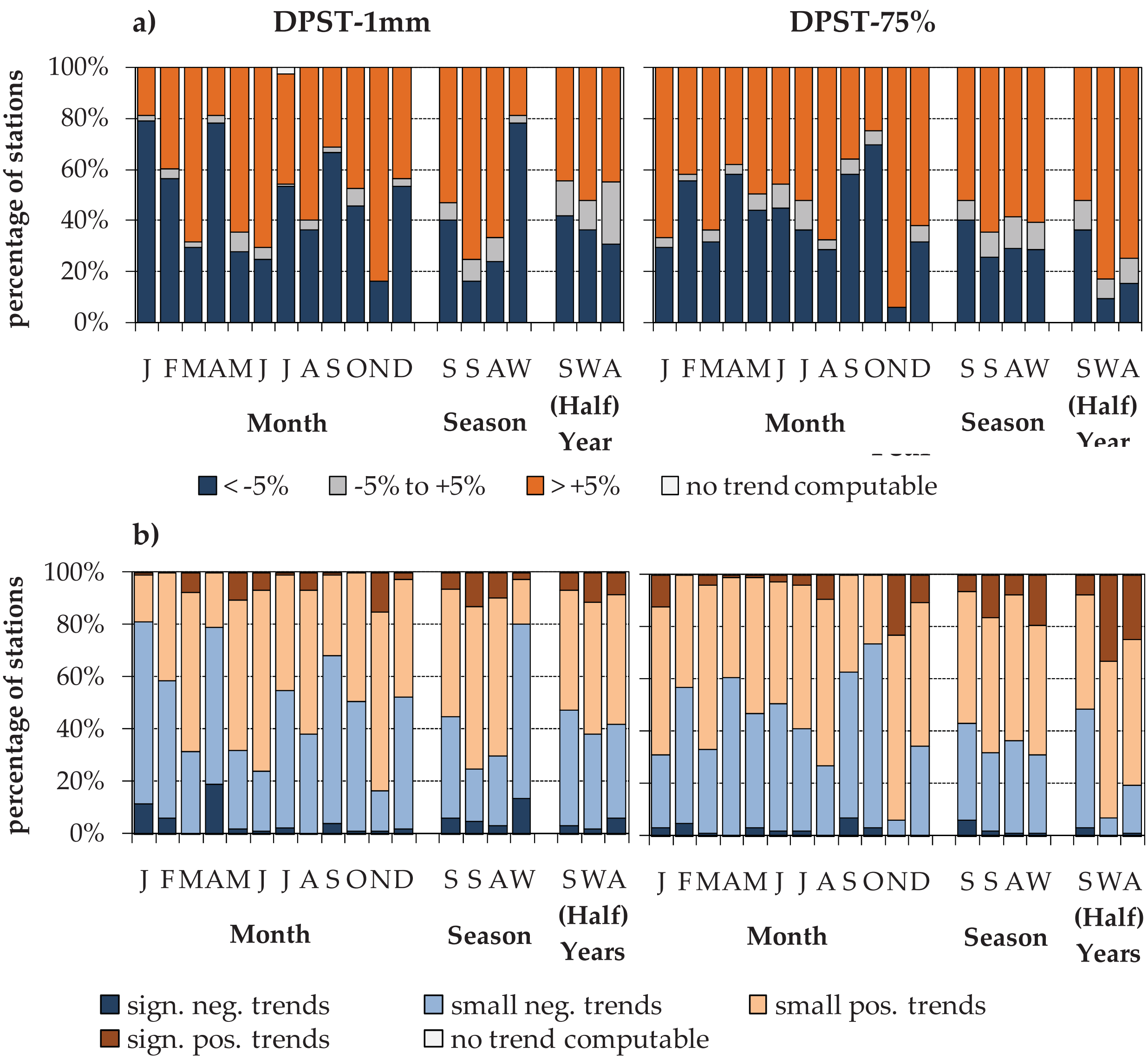


Figure 7.26: Percentage of stations with a) strong positive and negative linear trends and b) significant positive and negative trends according to the Mann-Kendall trend test for the frequency of DPST dry periods for 1951—2000

Positive summer half year trends may be found in all regions. According to the DPST-day-indicators, no region with predominant increases in summer drought exists. The half year trend patterns of the absolute and relative threshold are quite similar to each other.

Seasonally, the percentages of positive and negative trends of DPST frequency are very similar for the relative threshold (DPST-75%), but quite distinct for the absolute threshold (DPST-1mm; Figure 7.26). The frequency of DPST-1mm dry periods decreased at the majority of stations in winter, but predominantly increased during all other seasons with the highest percentage of positive trends in summer. In contrast to the predominately positive seasonal trends of DPST-frequency, most station trends of DPST-day-frequency (Figure 7.27) are

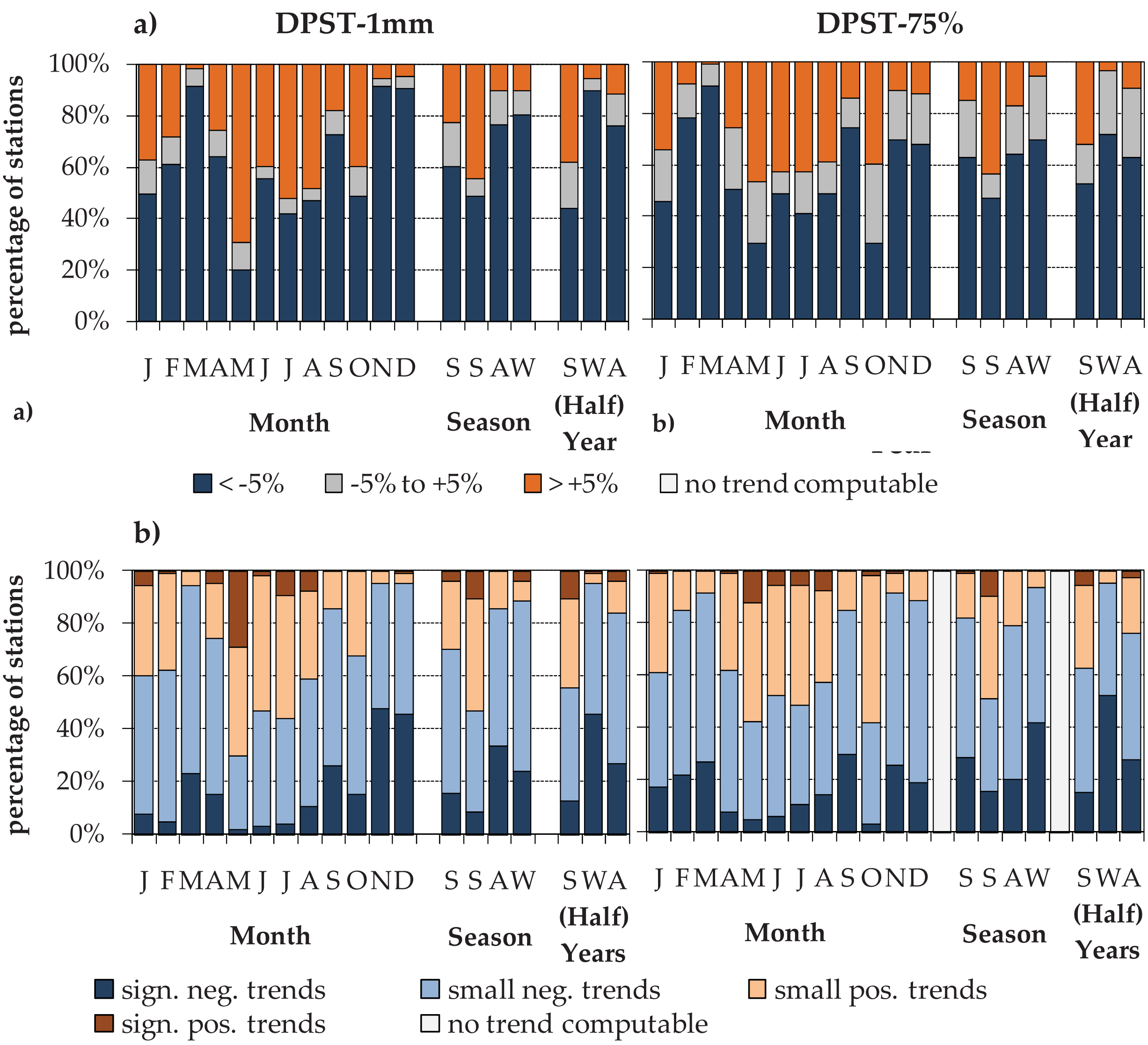


Figure 7.27: Percentage of stations with a) strong positive and negative linear trends and b) significant positive and negative trends according to the Mann-Kendall trend test for the frequency of days belonging to DPST dry periods for 1951—2000

negative indicating that they became less affected by droughts. This is true for both thresholds. Similar to DPST-frequency the frequency of days belonging to such events shows the highest percentage of positive trends during summer. Nevertheless, the percentage of negative trends is almost equal to the one of positive trends, indicating that there are no uniform changes in the extent, to which of the study area is affect by summer droughts, occurred during 1951—2000.

Even though monthly trends of DPST frequency have been calculated and displayed, they are not discussed individually, but only in combination with the trends of changes in the frequency of days belonging to such drought events. The rarity of DPST dry periods on a monthly basis strongly restricts the explanatory power of monthly trend analysis, which has already been

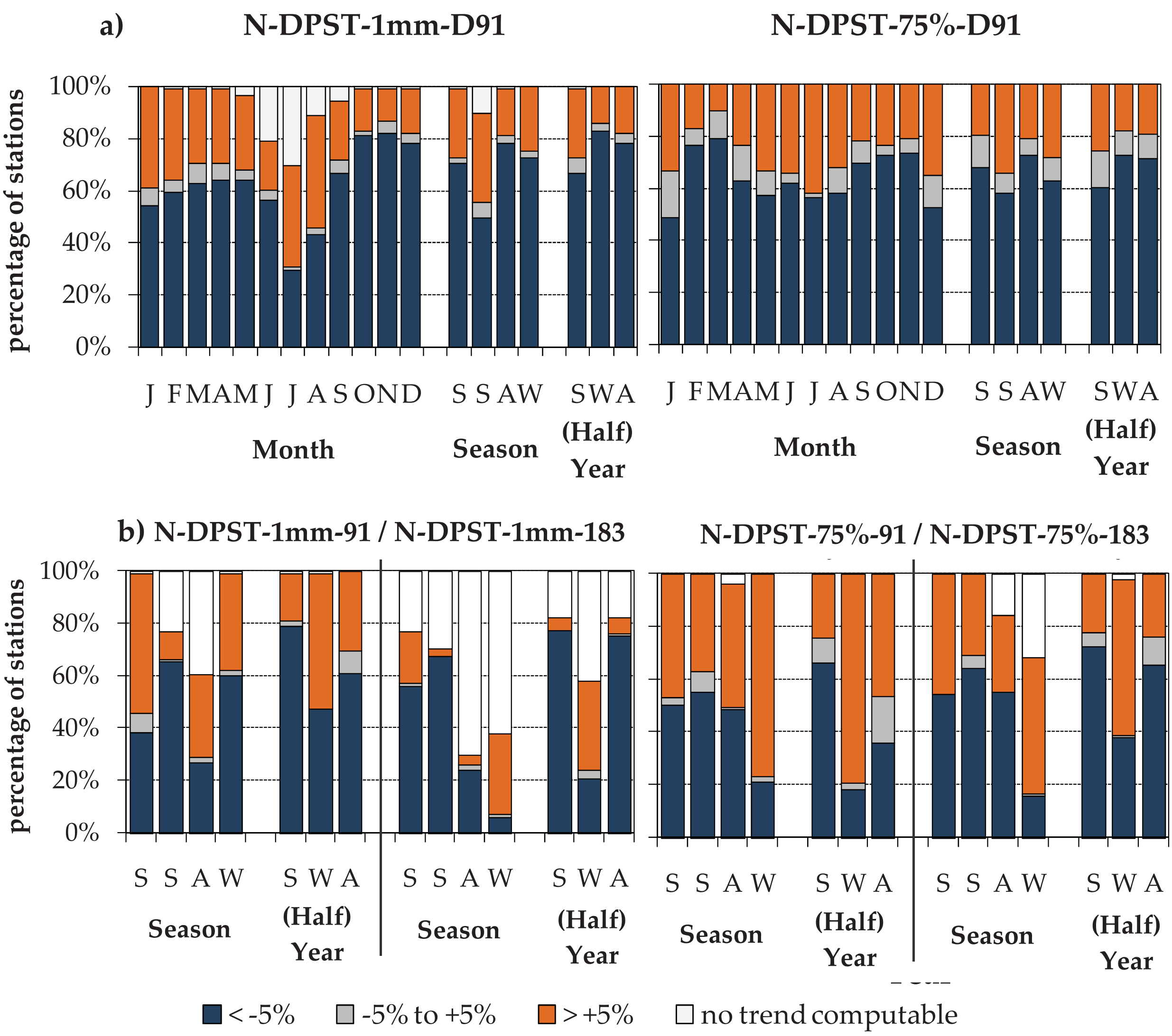


Figure 7.28: Percentage of stations with strong positive and negative linear trends for a) the frequency of days belonging to DPST dry periods lasting at least 91 days and b) the frequency of DPST dry periods lasting at least 91/ 183 days for 1951—2000

discussed in sub-section 7.2.1. The frequency of days belonging to DPST-1mm droughts has declined at the majority of stations in March and November (Figure 7.27), although DPST-1mm dry periods are more frequently terminated in those months (Figure 7.26). May, July and August are the only months for whom the increase in drought frequency is confirmed by the DPST-1mm-D trends at a majority of stations. Particularly for May, a high percentage of stations show statistically significant increases in the frequency of days belonging to DPST-1mm dry periods (Figure 7.27). The highest percentage of significant negative DPST-1mm-day trends occurs in November and December. This matches the general precipitation increases in those months.

The highest percentages of positive trends of days belonging to DPST-75% droughts were observed in May and October, although less DPST-75% dry periods occurred at the majority of stations in October (Figure 7.26). DPST-75% droughts are less often terminated in October, matching the general precipitation decreases in this month. Instead, they end more often in the following months that are characteristic for increasing precipitation totals. Like for the absolute threshold of 1 mm, the highest percentage of positive trends of DPST frequency was found in November. Using the days belonging to DPST dry periods as an indicator, November became less drought affected, despite the high increases in DPST frequency. The same is true for March that also shows distinct general precipitation increases. Most similar are the trends of the

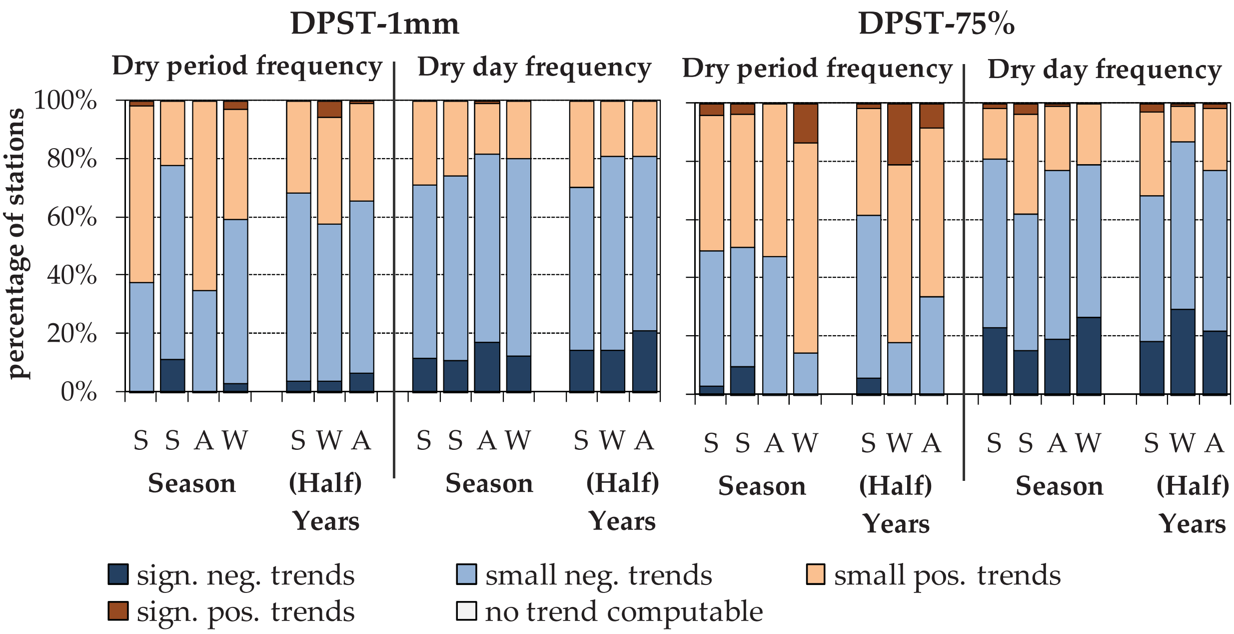


Figure 7.29: Percentage of stations with significant positive and negative trends according to the Mann-Kendall trend test for the frequency of dry periods as well as the frequency of days belonging to DPST dry periods lasting at least 91 days for 1951—2000

frequency of DPST dry periods and days belonging to such dry periods for May to August; compared to other months those months show a high percentage of positive trends for both indicators.

Long DPST dry periods lasting at least 91 or 183 days, respectively, occur very rarely. At some stations, no single event of such duration was observed in-some seasons. Thus, no trend calculation is possible for some stations and for the other stations, with only very few events, the trends are very sensitive to the timing of the drought events. Generally, the trends of such extreme drought events are not very reliable for short time scales as the 50 years analysed here, but in combination with the results of less extreme events, they might give some evidence for changes in the drought characteristics.

In contrast to the increasing frequency of DPST dry periods at the majority of stations (Figure 7.26), DPST droughts of at least 91 and 183 days, respectively, show more often negative station trends, particularly during the summer half year (Figure 7.28b). Generally the percentage of negative trends is higher first for DPST dry periods lasting more than 183 days compared to those of at least 91 days duration and secend for the absolute threshold in comparison to the relative one. This matches the observed decreases in the maximum duration of DPST droughts (sub-section 7.2.1) and supports the theory that long dry periods are more frequently interrupted by heavy precipitation events and periods and thus occur less frequent. This is also confirmed by the trend results of DPST-day-frequency, with predominantly negative trends in all months and seasons. The seasonal differences in the percentages of positive and negative trends of days belonging to long DPST dry periods are comparatively small (Figure 7.28a). A higher percentage of those negative trends of DPST day frequency is significant than compared to the positive ones of DPST frequency (Figure 7.29).

Decile dry periods: Slight decreases in the frequency of decile droughts have been observed during the 20th century (Figure 7.30). To meet with the obstacle of different data availability within individual periods, and thus different decile dry period numbers, the frequencies are extrapolated for a data availability of 100% at all stations per region. Differences in the magnitude of dry period frequency within individual regions are due to different numbers of stations contributing to the regional values. The observed decreases in decile drought frequency are most pronounced in the Southern and Western regions TFM, WEG, EEG and WSH.

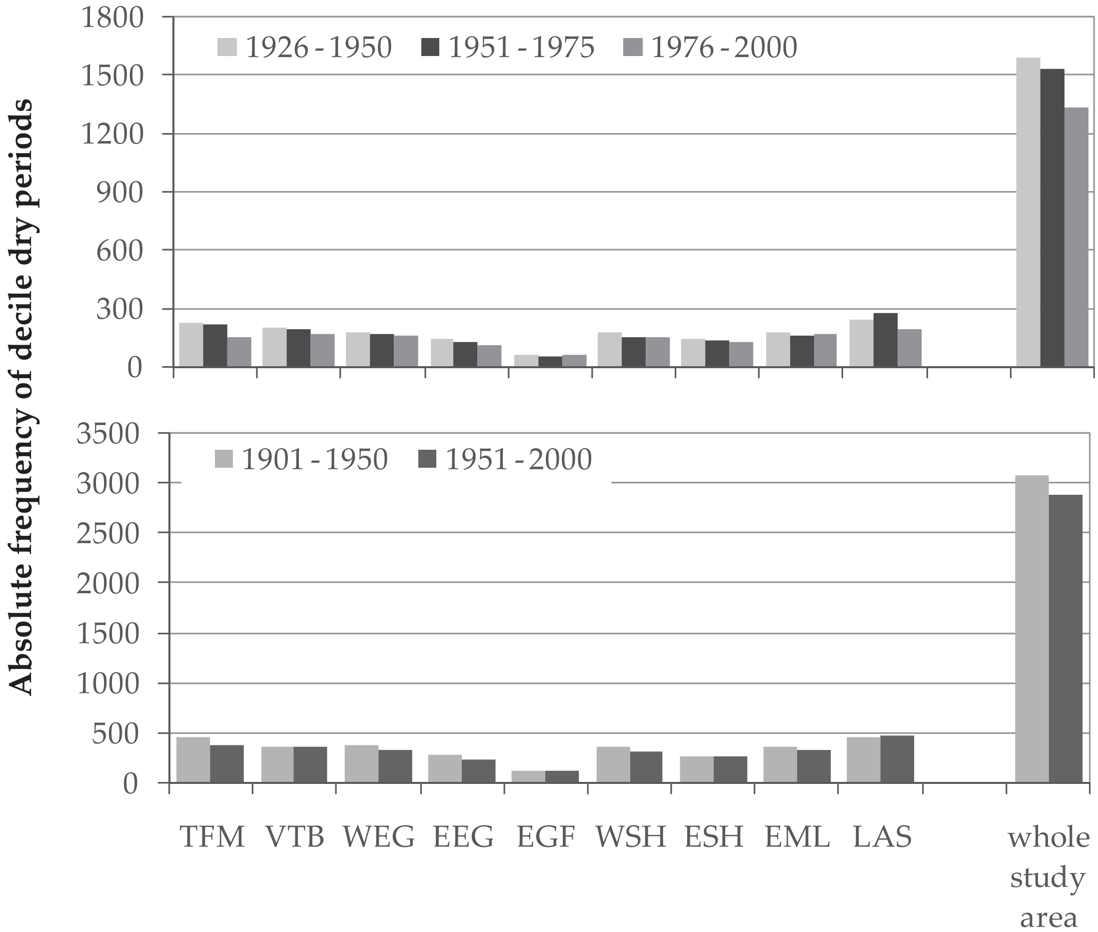


Figure 7.30: Changes in the absolute frequency of decile dry periods within the nine regions (130 stations) for 1901—2000 (results are extrapolated for 100% data availability)

7.2.3 Frequency and Severity of Drought Events

The frequency of severe dry periods is analysed on the basis of the monthly indicators RAI, PNI and the decile-indicator as well as based on daily indicators like meteorological dry periods and the adapted concept of meteorological droughts (DPST). A first overview about changes in the frequency of extremely dry and wet years/ months, respectively is given by Table 7.7 and Table 7.8 for the indicators RAI and PNI. Those tables classify the 15 driest months and years over the whole study area according to their timing into one of the three classes: A) first half of the 20th century/ 1900—1949, B) second half of the 20th century/ 1950—1999, and C) first years of the 21st century/ 2000—2006. The timing of the 15 driest months and years over the whole study area is indicated by different colours in the Table 7.7. The colour pattern of this table is quite similar for both indicators, as they identify the driest cases similarly. In the following Table 7.8, the information about the timing of dry and wet extremes is expressed in percentages of the total number of cases in each category.

Based on the PNI and RAI, more than twice as many of the driest years belong to period 1950—1999 as compared to 1900—1949 (Table 7.7, Table 7.8). This might be an evidence for an increasing frequency of extreme drought years in recent times. Most months, except May and December, show slightly higher percentages in the categories B and C compared to 1900—1949 matching the annual data. This observation is most pronounced for January to April and for

Table 7.7: Driest months and years (Ann) measured by the Percent of Normal indicator PNI and the Rainfall Anomaly Index (RAI) for the whole study area (130 stations) for 1900—2006

		Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percent of Normal Indicator (PNI)	1	1982	1996	1972	1943	1988	1990	1917	1971	2003	1959	1908	1902	1972
	2	1943	1972	1982	1921	1974	1992	1903	1904	1947	1948	1943	1920	1932
	3	2003	1997	1976	1984	1978	1918	1962	1990	1911	1982	1951	1953	1908
	4	1911	1971	1954	1950	1976	1980	1959	1964	1904	1929	1962	1931	1963
	5	1976	1990	2003	1929	1914	1947	1976	1991	1914	1947	1920	1946	1948
	6	1991	1919	1930	1954	2005	1909	1930	1952	1965	1969	1965	1962	1903
	7	1964	1904	1963	1959	1946	1934	1942	1969	1951	1961	1947	1986	1924
	8	1963	1903	1978	1932	1948	1919	1938	1943	1953	1997	1949	1958	1942
	9	1959	1924	1960	1942	2000	1988	1915	1911	1976	1923	1979	1929	1930
	10	1962	1964	1914	1953	1957	1989	1948	1928	1973	1991	1985	1948	1953
	11	1953	1991	1932	1974	1996	1943	2006	1983	1988	1973	1983	1982	1946
	12	1929	1963	1959	1976	1942	1998	2000	2006	1929	1945	1957	1918	1969
	13	1972	1989	1975	1964	2004	1915	1994	1935	1997	1917	1911	1997	1975
	14	1904	1978	1991	1903	1951	1979	1983	1976	1942	2006	1910	1967	1984
	15	1951	2006	1919	1991	1953	1922	2003	1949	1982	1933	1995	1955	1933
Rainfall Anomaly Index (RAI)	1	1982	1996	1972	1943	1988	1990	1962	1971	2003	1959	1943	1902	1972
	2	2003	1972	1982	1921	1974	1992	1917	1904	1947	1948	1908	1920	1932
	3	1943	1997	1954	1984	1978	1918	1959	1990	1911	1982	1951	1953	1963
	4	1911	1971	1976	1950	1976	1980	1903	1964	1904	1929	1962	1931	1908
	5	1976	1990	2003	1954	2005	1947	1976	1952	1965	1969	1965	1962	1948
	6	1991	1919	1930	1929	1914	1934	1942	1991	1914	1947	1920	1986	1903
	7	1964	1904	1963	1959	1946	1909	1938	1969	1951	1997	1947	1946	1953
	8	1963	1903	1978	1953	2000	1988	1930	1943	1953	1961	1949	1958	1924
	9	1959	1964	1960	1974	1948	1989	2006	1983	1976	1973	1979	1982	1942
	10	1962	1924	1914	1976	1957	1919	1948	1911	1973	1991	1985	1997	1930
	11	1953	1991	1932	1932	1996	1943	1915	2006	1988	1923	1983	1967	1946
	12	1972	1963	1975	1942	2004	1998	1994	1928	1997	1945	1957	1929	1975
	13	1929	1989	1959	1964	1942	1979	2000	1976	1982	2006	1995	1948	1969
	14	1951	1978	1991	1991	1951	1915	2003	1935	1979	1933	1911	1918	1984
	15	1904	2006	1927	1903	1953	1922	1983	1949	2001	1964	1987	1955	2000

Legend (cell shading): 1900-1949 (light grey), 1950-1999 (medium grey), 2000-2006 (dark grey)

July and August. Interesting is the high frequency of dry extremes in the most recent years (2000—2006) in months April and June with 3 cases each. In contrast, no single dry event within this time category has been observed for the months March, May, October and November. This does not necessarily have to mean that drought frequency decreased in those months, as the last period is with only 7 years much shorter than the 50-year intervals of 1900—1949 and 1950—1999. Therefore, the results of the last periods are much more influenced by coincidence.

The RAI and PNI indicators were also used to measure the severity of drought. Their magnitudes indicate the extent of dry and wet conditions. Additionally, the frequency of exceeding certain thresholds of those indicators standing for different drought severities was analysed. The trend analysis was done on a regional basis and not for individual stations, as severe drought conditions occur rarely at single station level. Different periods ranging from long term trends of 1901—2006 to short term trends of 1951—2006 have been analysed and compared.

On average, the annual RAI and PNI values have declined for period 1901—2006 (Figure 7.31, Table 7.9). Those decreases are even more pronounced during the SHY, while the WHY shows slight increases. This is in accordance with the general trends of precipitation totals. The annual and half year trends of mean RAI and PNI are quite similar, although the PNI is underestimating the dry extremes, particularly for the summer half year.

For shorter periods, like 1951—2006, the half year trends are similar to 1901—2006. In contrast, the annual trend of the average PNI values over all 130 stations is positive for the shorter period; due to the considerably larger winter half year trend as compared to 1901—2006 (Table 7.9). Such differences in the trends of different periods are also visible for monthly trends. While only February, March, November and December show increasing PNI averages for

Table 7.8: Comparison of the timing of the 15 driest months and years according to the Percent of Normal Indicator PNI and the Rainfall Anomaly Index RAI in Percent (the period with the highest percentage of dry cases is marked for every month)

		Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PNI	1900–1949	8.0	8.0	8.0	12.0	8.0	16.0	14.0	12.0	12.0	14.0	14.0	14.0	18.0
	1950–1999	20.0	20.0	20.0	18.0	16.0	14.0	10.0	16.0	16.0	14.0	16.0	16.0	12.0
	2000–2006	14.3	14.3	14.3	0.0	42.9	0.0	42.9	14.3	14.3	14.3	0.0	0.0	0.0
RAI	1900–1949	8.0	8.0	8.0	12.0	8.0	16.0	14.0	12.0	8.0	12.0	12.0	14.0	16.0
	1950–1999	20.0	20.0	20.0	18.0	16.0	14.0	10.0	16.0	18.0	16.0	18.0	16.0	12.0
	2000–2006	14.3	14.3	14.3	0.0	42.9	0.0	42.9	14.3	28.6	14.3	0.0	0.0	14.3

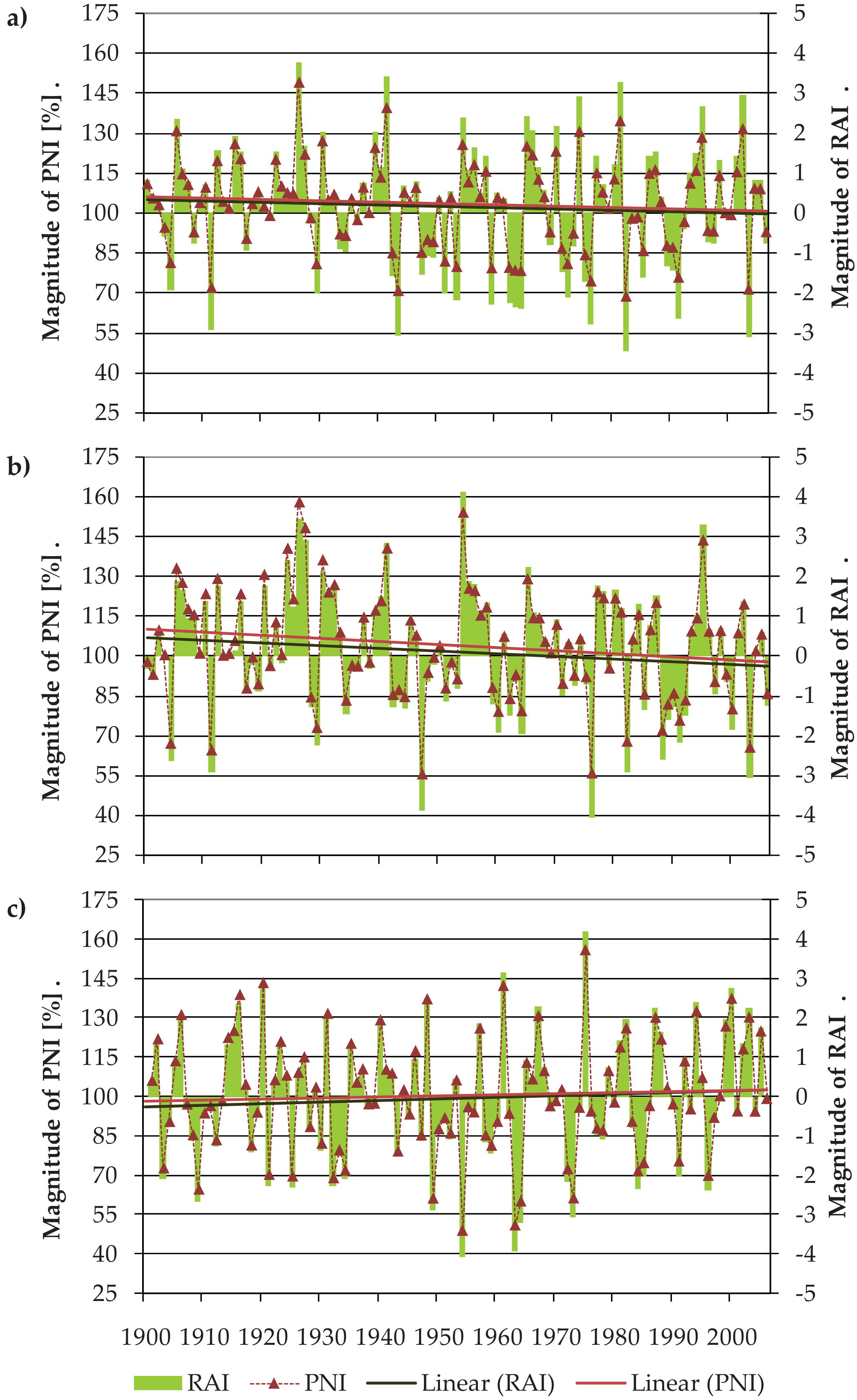


Figure 7.31: Time series of mean RAI (Rainfall Anomaly Index) and PNI (Percent of Normal Indicator) values with relative linear trends for a) the whole year, b) the summer and c) the winter half year for 1900—2006

1901—2006, the mean PNI trends of 1951—2006 are positive for January, August and September, too. In recent times, the trend to drier conditions is particularly pronounced from April to July.

Generally, the trends of the minimum RAI- and PNI-station values are very similar to each other and to the trends of their averages, particularly for period 1951—2006. Interesting are the trend results of minimum RAI for 1901—2006, indicating a tendency to higher negative deviations from normal conditions in all months and seasons except February. This trend might be biased by the station number, as the results are based on station values (namely the lowest RAI value out of all station RAI's) and the number of stations is increasing considerably in the 2nd part of the 20th century. Thus, the probability of reaching a low value, e.g., in periods where most stations show high RAI values, is increasing.

Next to the trends of mean and minimum PNI and RAI, the average trends of the exceedance frequency of several RAI- and PNI-thresholds are displayed in Table 7.9 for the periods 1901—2006 and 1951—2006. In most months, the trend pattern of both periods are quite similar. Most different are the trends of the two periods 1901—2006 and 1951—2006 in the months February, July and September as well as in the winter season.

Although the thresholds of the PNI and RAI indicators are not directly comparable, with respect to the severity of events above them, they give quite similar trend analysis results (Table 7.9). This may be due to fact that the trend direction seems to be quite independent from the severity of events the thresholds are indicating. With increasing moderate drought conditions, an increase in severe and extreme drought conditions becomes likely.

Generally, the exceedance frequency for RAI and PNI thresholds has decreased in most months and seasons for 1951—2006, whereas increases occur more frequent from 1901 to 2006 (Table 7.9). Exceptions occur most frequently for the rarest events, as for the 25%- PNI-threshold for and the -4- RAI-threshold. Such extreme drought conditions occur too infrequent for a reliable trend analysis and should be interpreted with great care. For some seasons, like spring and the summer half year no trend computation was possible for the lowest PNI-threshold, as no event below that threshold was observed. Thus, the interpretation should be based on the trends of moderate drought events.

A trend to more severe drought conditions for 1951—2006, using the exceedance frequency of RAI and PNI thresholds as an indicator, was found for the summer half year and spring as well as for the months January, April, May and August (Table 7.9). Although mean and minimum PNI/ RAI trends indicate more severe drought conditions in July and October, the PNI/ RAI thresholds

Table 7.9: Monthly and seasonal relative linear trends for the frequency of falling below individual thresholds of RAI (Rainfall Anomaly Index) and PNI (Percent of Normal Indicator) for period 1901—2006 in comparison to 1951—2006

		PNI					RAI			
		Mean	No. < 75%	No. < 50%	No. < 25%	Min	No. < -2	No. < -3	No. < -4	Min
1901—2006	January	-6.0	17.1	100.0	345.1	-15.0	73.4	242.4	419.3	18.4
	February	7.0	-15.2	23.9	188.9	9.0	17.3	172.2	201.2	-4.1
	March	16.7	-32.7	-49.3	-89.1	0.7	-19.9	-0.5	58.4	11.6
	April	-15.6	25.0	72.1	207.7	-29.0	75.6	179.3	324.5	31.6
	May	-4.0	6.3	1.9	55.6	-5.5	30.5	93.7	374.0	19.2
	June	-11.7	3.5	-1.5	-128.3	-22.0	26.8	-2.2	49.8	30.0
	July	-23.4	33.5	46.3	11.4	-35.5	53.7	89.9	58.2	56.2
	August	-9.2	57.0	9.2	-97.6	-20.5	48.7	-9.8	193.2	32.8
	September	-7.8	4.7	29.7	79.0	-14.9	41.4	100.1	64.9	22.4
	October	-19.6	30.0	5.5	-88.9	-25.4	11.9	-68.3	-20.5	45.0
	November	10.5	-47.5	-79.7	-241.1	10.6	-57.3	-111.4	-289.1	2.3
	December	16.6	4.4	-51.2	-156.7	12.7	-23.5	-87.0	204.9	4.4
	Spring	-1.6	-8.3	-14.1	-117.8	-0.7	23.5	72.0	148.8	23.2
	Summer	-14.7	14.7	-189.2	-368.0	-20.8	26.4	-32.5	-123.8	65.9
	Autumn	-5.9	-4.0	-33.2	-213.6	-1.7	-3.2	8.9	-0.1	23.4
	Winter	6.4	8.4	89.4	192.6	3.0	34.0	124.3	175.8	5.2
	SHY	-12.1	57.6	96.0	#####	-13.5	77.2	71.6	163.9	53.1
	WHY	4.4	-22.7	17.3	5.6	-0.4	-13.2	13.6	52.1	7.2
	Annual	-5.2	50.8	-238.4	#####	-0.5	46.4	99.1	235.3	14.1
1951—2006	January	9.1	6.5	88.8	164.9	26.5	59.3	119.5	278.3	-24.8
	February	25.7	-45.1	-80.3	-76.2	54.9	-77.0	-90.1	-148.6	-52.0
	March	35.9	-34.2	-90.1	-66.1	60.9	-72.3	-103.3	35.2	-54.7
	April	-27.8	48.4	67.3	47.2	-19.3	64.1	43.7	159.5	19.4
	May	-7.4	16.3	105.0	185.3	-16.8	84.2	166.2	201.8	9.1
	June	-24.4	36.7	35.5	-63.4	-14.5	36.2	-9.9	-110.2	11.0
	July	-16.8	-36.4	-32.6	-53.1	-23.9	-28.8	-38.5	-11.5	4.4
	August	14.3	7.2	15.0	147.5	28.7	16.1	25.4	207.8	-16.9
	September	1.7	-38.1	-30.6	-91.3	6.4	-33.2	-76.7	-376.8	-12.0
	October	-15.1	-14.8	-57.7	-258.4	-12.3	-61.0	-285.5	-521.4	6.0
	November	45.3	-82.5	-169.9	-272.0	90.1	-147.1	-228.3	-470.2	-81.3
	December	16.8	-23.6	-133.9	-209.0	21.3	-114.9	-210.9	-141.7	-21.8
	Spring	-0.7	8.0	84.3	#####	-0.3	12.5	59.6	32.9	1.4
	Summer	-9.6	-19.4	6.7	-52.6	-10.1	-22.3	-14.4	-31.9	14.6
	Autumn	10.6	-58.7	-214.5	-267.4	19.1	-97.6	-195.2	-246.8	-40.9
	Winter	19.5	-57.4	-89.5	-164.7	19.9	-55.9	-53.9	-72.5	-21.7
	SHY	-10.1	86.7	145.8	#####	-13.5	66.5	93.2	105.6	27.1
	WHY	20.0	-127.8	-384.5	-515.8	20.7	-124.4	-236.4	-398.8	-53.4
	Annual	2.6	-48.5	73.7	#####	3.2	-76.6	-33.2	30.3	-17.4

less frequent dry extremes (blue) ##### no trend computation possible

more frequent dry extremes (orange)

are exceeded less frequent within those months. Severe drought events do not seem to occur more frequent in July and October, despite negative precipitation trends.

Exemplary for the temporal trend characteristics of drought indicators the dependencies of RAI and PNI trends on the period chosen for trend calculation are displayed in Annex 22. The tables of Annex 22 furthermore illustrate the regional trend characteristics for individual periods. The comparison of the trends of periods 1901—2000, 1931—2000, 1941—2000 and 1951—2000 shows that generally the trends of 1901—2000 are most different from those of the other periods. The differences in the trend pattern of 1901—2006 and 1951—2006 have already been illustrated in the precious paragraphs (Table 7.9). The trends of the periods lasting until 2000 are quite similar to those lasting 6 years longer. Nevertheless, in some months and seasons a regional intensification of positive or negative trends occurred. For example, the frequency of severe drought events in April and August shows regionally more frequent increases for the periods ending 2006 in comparison to those lasting only until 2000.

The temporal representativeness of trends is quite different in individual months and seasons. Most similar are the trend pattern of different periods for the months January, March, April, May, November and December. In contrast, the trend patterns of the winter half year as well as those of the seasons autumn and winter are very different for individual periods, particularly for the secular trends. On a monthly basis the PNI and RAI trends are least temporally representative in February and September. For both months predominantly positive trends were calculated for the longest and predominantly negative trends for the shortest periods.

Regionally, trends to more frequent severe drought events occur more often in the regions of lower altitude in the North and East of the study area, namely Western and Eastern Saxon Hilly Country (WSH, ESH), 'Elbe Mulde' Lowlands (EML) and 'Lausitz and Spreewald' (LAS). The Erzgebirge regions (WEG and EEG) show most often different trend directions than the other regions. They seem to be at least at risk to be affected by more frequent and severe drought events according to the 'Percent of Normal Indicator' (PNI) and the 'Rainfall Anomaly Index' (RAI).

RAI and PNI deliver aggregated information for the period they are calculated for, like individual months, seasons or years. No information about the persistence of dry conditions may be derived at first go. Therefore, those indicators are not suitable to make conclusions about changes in the frequency of dry periods, but just of dry events. Direct comparisons to the trend results of the decile indicator providing long term dry periods are not possible.

7.2.4 Timing of Drought

The timing of decile droughts is connected to the trends of monthly precipitation totals, but no direct relationships are visible at first glance, as the decile indicator is based on three month totals and thus averages the possibly opposite precipitation trends of consecutive months. The first month of the first three-month total of a decile dry period is assigned to be the starting month, while the end of a decile drought is assigned to the last month of the last three-month total within the dry period.

Although there have been some shifts in the characteristic months in which decile dry periods frequently start or end the general characteristic described in 6.2.3 stayed the same. While at the beginning of the 20th century (1901—1950, and 1926—1950) decile droughts started most often in September and November, they begin more frequent during the winter months in recent times (1975—2000, and 1950—2000; Figure 7.32). Even within the second part of the 20th century a shift from autumn to winter is visible. In contrast, decile droughts

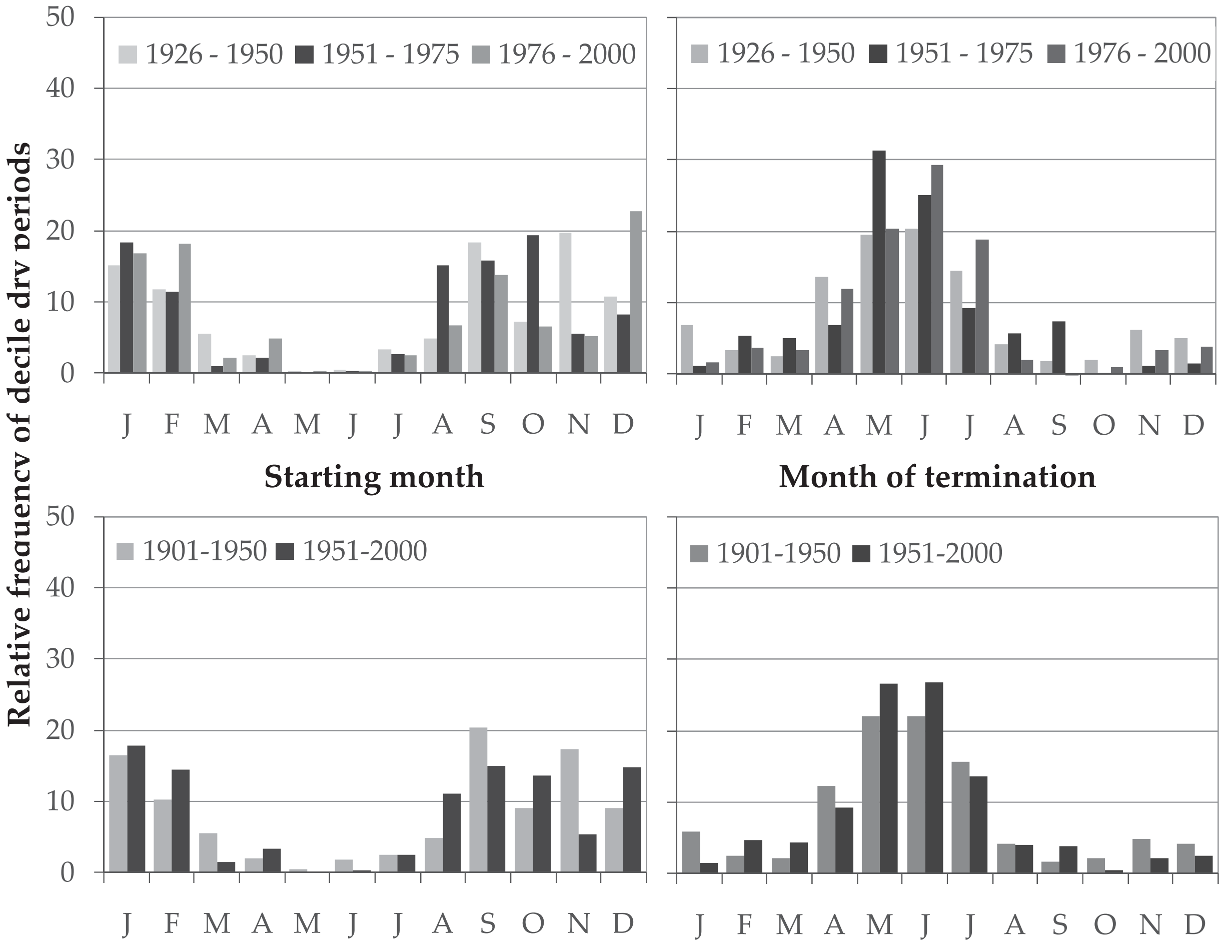


Figure 7.32: Shifts in the characteristic months of decile dry periods start and termination in nine regions in South Eastern Germany (130 stations) for 1901 to 2000

end less often in winter in recent times (Figure 7.32). The distribution of the characteristic drought termination months shifted to higher frequencies in May and June at the end of the 20th century.

7.2.5 Spatial Drought Characteristics

The spatial characteristics of decile droughts have undergone major changes within the 20th century. From 1900 to 2006, the spatial coverage of drought events has increased by about 6%, while for the shorter time intervals a trend reversal occurred to strong negative trends (Figure 7.33).

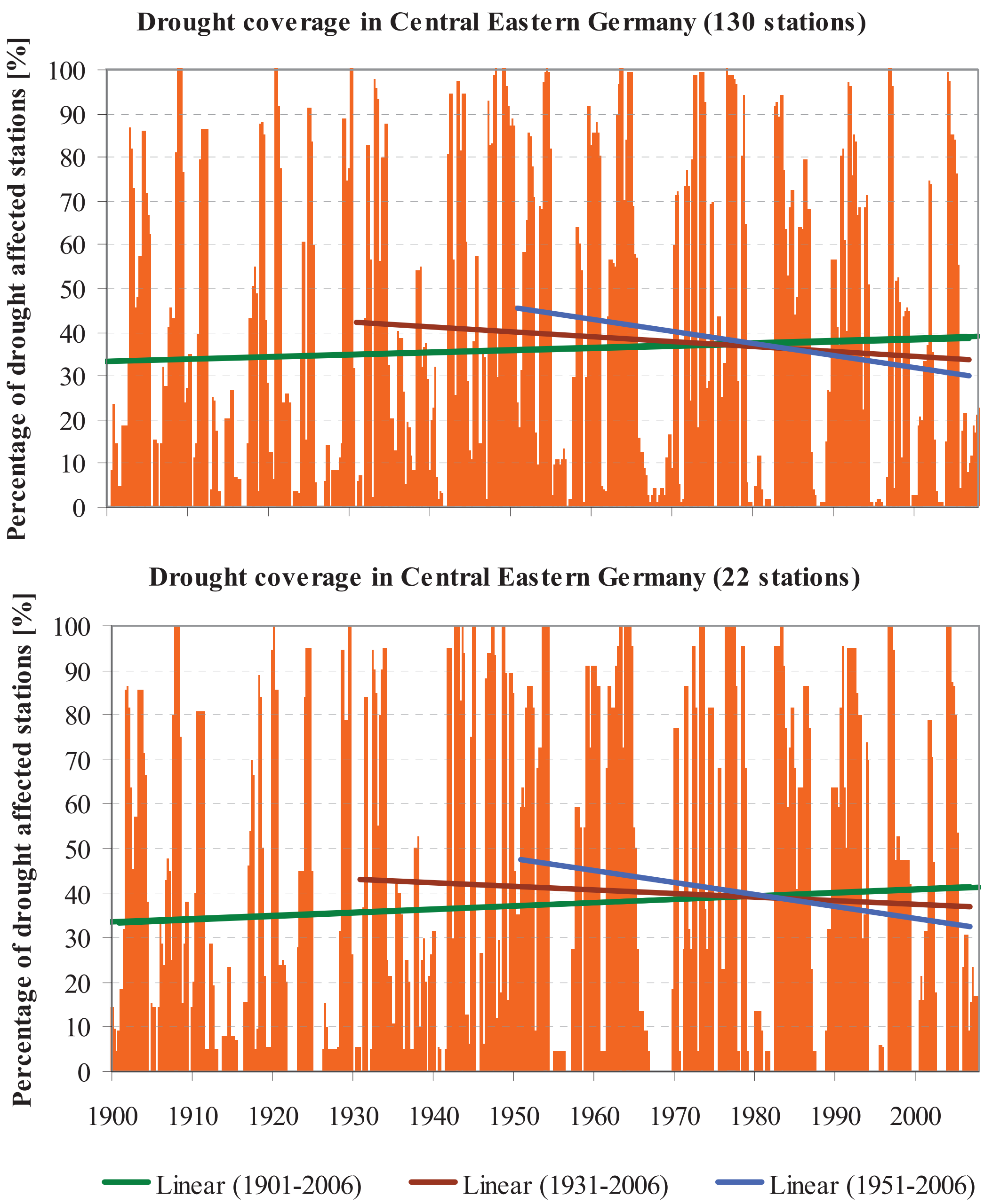


Figure 7.33: Drought coverage measured by the decile indicator for a) the whole study area (130 stations) and b) 22 stations with long time series for 1900—2006

Due to the poor data availability at the beginning of the 20th century, the long term trend is the least reliable one. It might be influenced by chance, as outliers (station with no decile drought at times of high decile drought coverage and vice versa) have a greater impact on the percentage of drought affected stations. Nevertheless, the observed trends of drought coverage changes seem to be realistic, as the results are almost the same for different data base. Using only the 22 stations that have data available as of 1901 instead using all 130 stations has no major influence on the spatial decile drought characteristics and trends (Figure 7.33).

The changes in the regional coverage of decile droughts are quite similar within all regions (Annex 23). All regions apart from the northernmost region EML (Elbe-Mulde Lowlands) show this trend reversal from slightly positive trends for 1901—2006 to strong negative trends for 1951—2000. In region EML the 1901—2006 trend is already slightly negative. For the 'Thuringian-Franconian Mountains' (TFM), no trend may be computed for 1901—2006, since the earliest station time series within this region started in 1931.

In the second part of the 20th century, decile dry periods seem to be considerably less regionally extended. This might be due to changes in the atmospheric circulation pattern that trigger drought conditions in the study area. Possibly dry periods are regionally more often interrupted by small scale periods with above average precipitation. The observed trends might give evidence for the increasing frequency and influence of local convective precipitation events.

7.2.6 Resume

Changes in frequency, intensity, duration and spatial extension of drought events were analysed, using several drought indicators, based on monthly and daily precipitation totals. The intensity of drought conditions was studied using the indicators 'Percent of Normal Indicator' PNI and the 'Rainfall Anomaly Index' RAI that are based on monthly data. Indicators describing dry periods of different duration were calculated based on daily (DP, DPST) and monthly data (decile droughts). Dry period durations were assigned to the month, season or year, respectively, in which the drought is terminated. Thus, the monthly and seasonal trend results of DP and DPST duration are strongly biased to the month of their termination. To receive more robust information about the extent to which single months and seasons were affected by drought conditions, the frequency of days assigned to a dry period (DP-D and DPST-D) was analysed. The trend results of DP and DP-D frequency were similar, due to the short duration of DP events lasting normally less than a month. In contrast, great differences occured for the longer lasting DPST droughts.

Annually DP and DPST events became shorter in most regions for 1951—2000, most significant in the region TFM. Small decreases in the average duration of decile dry periods confirm this general decrease in drought duration in the second half of the 20th century that seems to be quite independent from the timescale over which drought conditions are averaged by individual indicators. Nevertheless, decile droughts were considerably shorter in the first half of the 20th century, indicating some long-term increase in drought duration. As the daily indicators DP and DPST were only calculated as of 1951, they cannot confirm those results. Small increases in average and maximum annual DP duration were observed in Eastern Saxony (LAS) only, the region with the most pronounced increases in decile drought duration.

The negative DP duration trends for the SHY were highest in the north-eastern regions EML and LAS matching the strongest precipitation decreases in the SHY within those regions. The positive SHY trends were significant at a high percentage of stations for May and August. Most significant decreases in DP duration were observed for March, April and October. The distinct precipitation decreases in April and October do not seem to further aggravate the drought conditions in those months. In contrast to the DP trends, the DPST indicators suggested predominantly decreasing drought durations in both half years, being significant at a higher percentage of stations during the SHY. Due to the longer durations und thus considerably lower frequencies of DPST compared to DP droughts, their seasonal and monthly trends were less robust and significant.

Annual DP frequency trends are comparatively small and regionally indifferent, with slightly more negative than positive trends. Seasonally opposite developments occurred for the frequency of DP and DP-D. During the SHY, in particular in May and August, more frequent short meteorological dry periods (DP) occurred. The decreases in DP frequency during the WHY were most pronounced in March, November and December and for DP-D frequency additionally in February and October. Most significant were the DP-D trends of March, May and October.

The annual frequency of decile droughts and of DPST-D decreased, while more frequent DPST events were observed at the majority of stations, particularly for the relative threshold of 75% of daily normal precipitation. Similar tendencies were found in both half years, that both show increases in DPST-frequency and decreases in DPST-D-frequency. Nevertheless, more stations indicate increasing drought conditions during the SHY than during the WHY. Positive DPST-D trends are most frequently significant for May, while a high percentage of significant negative trends were observed in March, September, November and December. The simultaneous decrease in duration and increase in frequency of DPST for 1951—2006 might give evidence for a more frequent interruption of dry periods by days and periods of above average precipitation in recent times. Significant decreases in the regional coverage of decile drought during that period confirm the probably increased influence of small-scale precipitation on drought occurrence and termination. Changes in the atmospheric circulation pattern that trigger drought conditions within the study area are likely to occur.

A higher percentage of the most extreme dry years, according to the indicators PNI and RAI, was observed in the second part of the 20th century and the first years of the 21st century. This is true for most months, except for May and December. Dry extremes occurred very frequently in recent years in April and June. In most months and seasons, the trend direction of the frequency of differently severe dry events seems to be quite independent from the severity of events. The annual PNI and RAI averages declined and the frequency of exceeding certain RAI and PNI thresholds increased for 1901—2006, suggesting more frequent severe drought conditions. In contrast, trends for the more recent period of 1951—2006 indicate slight annual decreases in drought severity and frequency. Similar tendencies were found for many months and seasons; long-term trends more frequently indicate increasing drought conditions than short-term trends. Decreases in drought frequency and severity mainly occurred in March, November and December, characterised by the highest and most significant precipitation increases. This is true for all investigated periods. In contrast pronounced increases during most periods occurred in April and May, matching the general precipitation decreases. Despite their pronounced precipitation decreases, June and October do not seem to be considerably more affected by severe droughts. Furthermore, their trends are temporarily less representative than those of March, April, May, November and December. The RAI and PNI trends for February and September were least temporally representative.

Most indicators suggest a tendency to less frequent and shorter drought events particularly in 1951—2000, although the frequency of monthly and annual dry extremes increased for 1901—2006. The SHY is more frequently characterised by trends towards more frequent, severe and longer lasting dry periods, matching the summerly precipitation decreases. Opposite tendencies were found for the winter half year. Nevertheless, opposite trends of individual indicators are possible, due to the different related time scales. Short meteorological dry periods (DP) lasting only a few weeks, for example, increased in frequency and duration during the SHY, while they showed negative trends for the WHY. In contrast the duration of DPST dry periods lasting several months decreased at a high percentage of stations for both half years, while their frequency increased during the SHY and decreased during the WHY. Seasonal and monthly trends were less robust and significant for longer drought events than for shorter ones. Observed shifts in the timing of drought events (onset and termination) are probably due to changes in average precipitation totals.

7.3 Trend Analysis of Wet Period Indices and Heavy Precipitation Events

All 130 rain gauge stations, displayed in Figure 7.34, were used for the analysis of wet events and periods, using monthly precipitation time series. Heavy precipitation analysis based on daily precipitation data was done for 112 selected stations with a high quality data coverage in period 1951—2000. Trend analysis was carried out for those stations only that had at least 90% of the time series elements per investigated period available. Monthly heavy precipitation indicators were computed, if less than 4 days were missing. Annual and seasonal values were only calculated, if all months fulfilled this criterion.

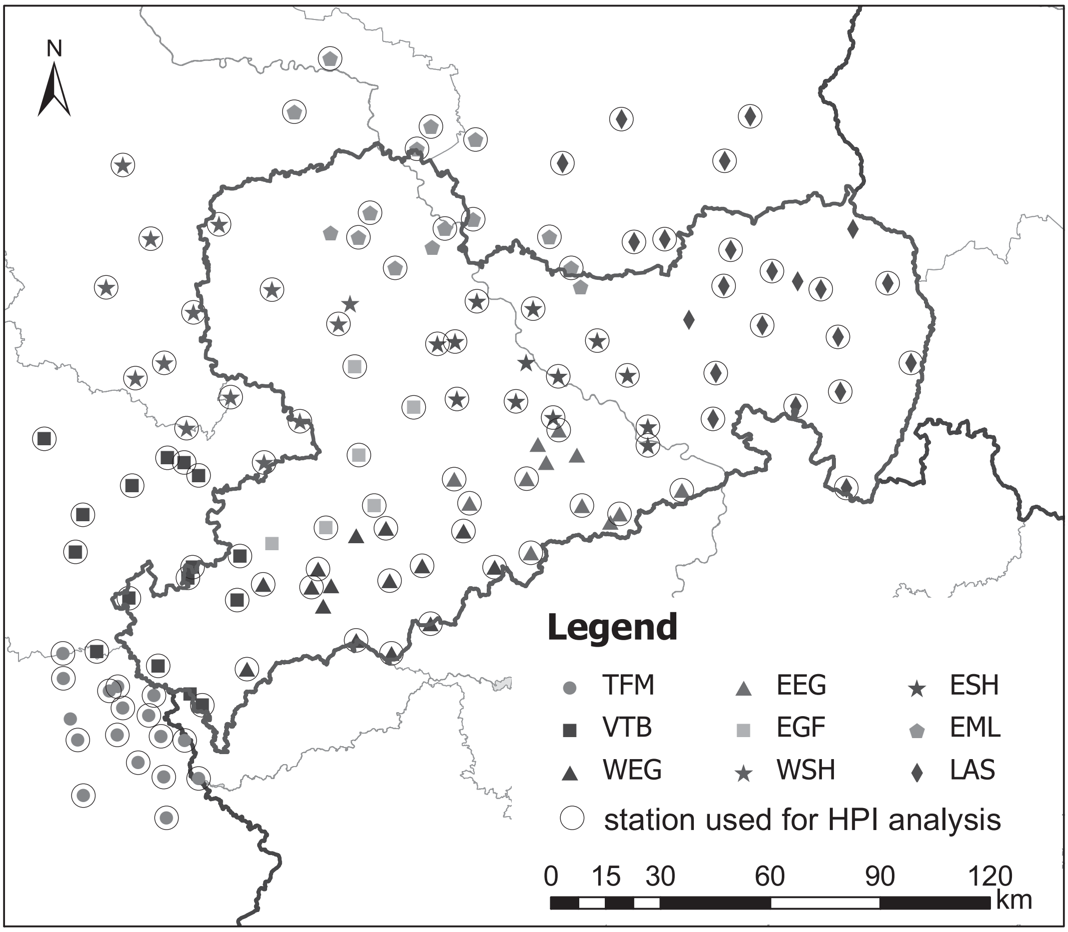
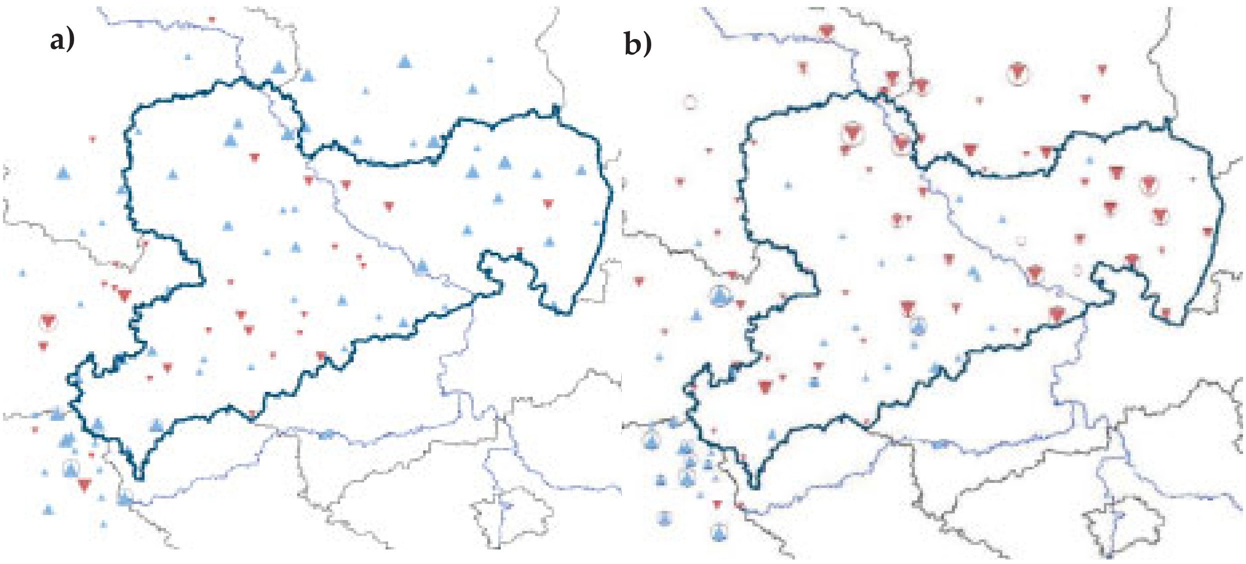


Figure 7.34: Map of all stations with labels for those used for the trend analysis of Heavy Precipitation Indicators (HPI) in the individual regions

7.3.1 Changes in the Characteristics of Average Daily Precipitation Indices

The trends of some more basic indicators are studied, before analysing the magnitude and frequency of extreme daily precipitation. Those indicators, describing average precipitation conditions, are 1) the frequency of dry, wet and rain days, 2) the Simple Daily Precipitation Index, 3) the average precipitation intensity on days above the 95th percentile and 4) the percentage of precipitation above the 95th percentile on total precipitation. Altogether, 112 stations with daily precipitation data were included in the trend analysis of daily Heavy Precipitation Indices (HPI). Regional averages of these station trends were computed and compared. The significance of trends was tested using the non-parametric and non-linear Mann-Kendall trend test. Please note that the significance information of the Mann-Kendall trend test does not refer to the magnitude of the linear trends. Both concepts of trend calculation were used complementary, to preferably receive robust information about changes in heavy precipitation characteristics. Trend analysis was done for periods of different lengths, ranging from the longest period of 1931—2006 to the shortest period of 1951—2000. Additionally, the temporal representativeness of trends was studied, using a moving 30-year trend analysis.



Relative linear trends [%]:
magnitude 0.1-5 5.1-10 10.1-25 25.1-50 > 50.1
direction positive negative wetter drier
Mann-Kendall trends:
significance $\alpha = 0.2$ $\alpha = 0.1$ $\alpha = 0.05$ $\alpha = 0.01$ $\alpha < 0.001$

Figure 7.35: Map of the annual linear trends of a) the frequency of wet days (N-WD) and b) the Simple Daily Precipitation Intensity indicator (SDPI) for 1951—2000

1) Frequency of wet days: Annually, most stations show an increasing frequency of wet days during most periods (Figure 7.35a, Table 7.10). Those increases are mainly due to positive winter half year trends, while for the summer half year negative trends predominate. About half of the station trends of 1951—2000 for the summer half year and more than 60% of the winter half year trends are statistically significant according to the Mann-Kendall trend test (Figure 7.36).

Mainly autumn and winter contribute to the increasing annual frequency of wet days, whereas deceases in wet day frequency have been observed for summer (Table 7.10). Compared to the half year trends, less stations show significant seasonal trends (Figure 7.36). Least changes have been observed for spring. This is probably due to opposite monthly trends. While March is characterised by regionally very homogenous, large positive trends, the opposite is true for April and May. High percentages of negative trends were also observed for August. The decreases in wet day frequency for period 1951—2000 are statistically most significant for August and May (Figure 7.36). In November and December, the majority of stations showed trends towards an increasing frequency of wet days for all investigated periods. High percentages of positive Mann-Kendall station trends occurred in March and November.

Generally, the trends in the different periods are quite similar. This is particularly true for the months and seasons with highly significant changes like both half years, March, May, August and November. In contrast, the months January, February, June, July and October show trend reversals from the longer to the shorter periods. Apart from June and July, higher percentages of negative trends were observed for the longer periods. More pronounced trends toward less precipitation have been already described for the longer timeframes for precipitation totals (sub-section 7.1.1). Nevertheless, it is still possible that the long term trends are more affected by outliers, as the percentages of the longer periods are based on considerably less stations than those of periods starting in 1951.

The trends of dry and rain day frequency (Annex 24 and Annex 25) are very similar to those of wet days discussed here (Table 7.10, Figure 7.36). Therefore, only the differences are illustrated. The largest deviations have been observed for monthly trends of the shorter periods, in particular for rain days. Rain days show lower percentages of negative trends during the summer months June and August. Days with precipitation above 2 mm have increased significantly at more than 20% of the stations in those months, while almost no significant negative trends were observed for 1951—2000.

Table 7.10: Average linear trends and percentage of positive and negative station trends of wet day frequency (N-WD: Pd ≥ 1 mm d^{-1}) for individual periods (1931/ 1941/ 1951 to 2000/ 2006); trends towards more/ less (extreme/ frequent) precipitation are marked by blue/ orange colour, percentages of station trends above 66.67% are marked bold

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	55	45	0.3	63	37	5.3	63	38	8.8	**68**	32	14.7	38	63	-5.9	**67**	33	6.6
Feb	**91**	9	21.4	**97**	3	26.1	33	**67**	-9.0	45	55	0.5	13	**88**	-24.9	36	64	-10.7
Mar	**99**	1	39.4	**100**	0	34.7	**100**	0	38.7	**95**	5	38.2	**100**	0	30.2	**92**	8	31.9
Apr	16	**84**	-13.6	5	**95**	-24.0	25	**75**	-9.0	0	**100**	-18.7	20	**80**	-10.1	8	**92**	-22.0
May	19	**81**	-14.8	22	**78**	-9.0	0	**100**	-23.7	5	**95**	-18.3	6	**94**	-16.9	8	**92**	-12.4
Jun	28	**72**	-12.7	6	**94**	-21.0	54	46	0.4	18	**82**	-9.0	**67**	33	4.0	31	**69**	-4.7
Jul	22	**78**	-21.5	23	**77**	-15.0	46	54	-2.7	41	59	-4.0	19	**81**	-12.9	31	**69**	-8.3
Aug	60	40	4.7	**70**	30	9.6	**79**	21	11.7	**82**	18	16.6	50	50	-0.6	62	38	6.0
Sep	59	41	2.0	**69**	31	6.9	**96**	4	17.9	**95**	5	24.9	**81**	19	11.4	**83**	17	21.3
Oct	15	**85**	-17.0	19	**81**	-12.6	54	46	2.4	55	45	5.9	25	**75**	-30.6	42	58	-19.2
Nov	**96**	4	32.5	**99**	1	42.2	**96**	4	21.0	**100**	0	32.7	**75**	25	9.3	**92**	8	24.5
Dec	**98**	2	20.8	**96**	4	18.1	**100**	0	29.6	**100**	0	26.2	**100**	0	40.5	**100**	0	41.0
Spr	57	43	1.6	49	51	-0.5	50	50	-0.3	48	52	-1.0	40	60	-0.5	30	**70**	-3.0
Sum	23	**77**	-10.4	19	**81**	-8.8	**67**	33	2.9	64	36	0.9	36	64	-2.9	42	58	-2.5
Aut	**68**	32	5.8	**86**	14	12.5	**83**	17	13.7	**95**	5	20.5	40	60	-3.2	**73**	27	10.1
Win	**88**	12	16.8	**91**	9	17.4	**82**	18	14.2	**79**	21	16.7	**67**	33	12.3	**88**	13	23.1
SHY	16	**84**	-9.6	12	**88**	-8.3	57	43	-0.7	57	43	-1.2	23	**77**	-4.4	27	**73**	-3.6
WHY	**93**	7	18.3	**98**	2	19.3	**86**	14	19.2	**88**	12	23.8	50	50	8.8	**88**	13	20.6
Ann	56	44	1.4	64	36	3.4	**76**	24	6.9	**76**	24	8.4	42	58	-0.3	**75**	25	5.3

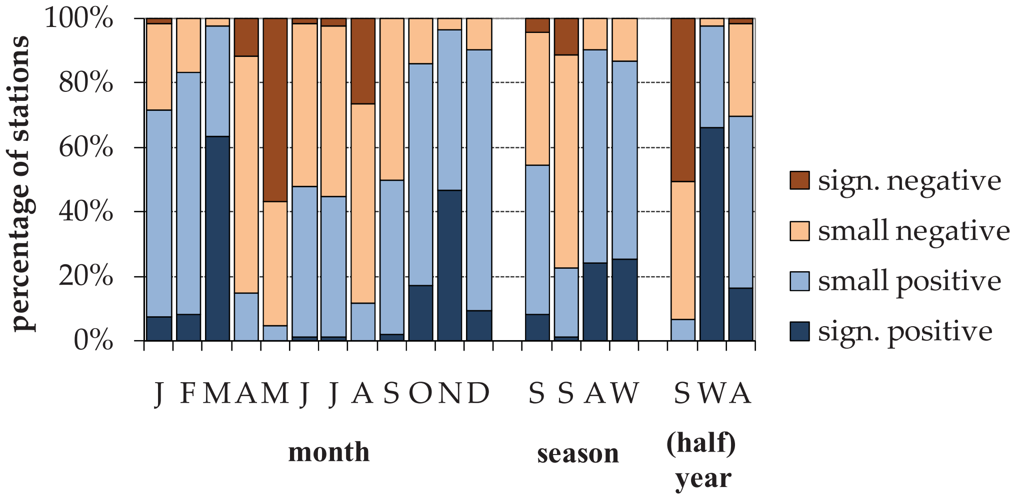


Figure 7.36: Percentage of significant positive and negative trends (Mann-Kendall trend test, $\alpha \leq 0.2$) for the frequency of wet days (N-WD: Pd ≥ 1 mm d^{-1}) for 1951—2000

Table 7.11: Average linear trends and percentage of positive and negative station trends of the Simple Daily Precipitation Intensity index for individual periods (1931/ 1941/ 1951 to 2000/ 2006); trends towards more/ less (extreme/ frequent) precipitation are marked by blue/ orange background colour, percentages of station trends above 66.67% are marked bold

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	18	**82**	-12.9	31	**69**	-5.8	54	46	-1.7	59	41	6.1	19	**81**	-13.0	42	58	-1.1
Feb	**92**	8	14.6	**95**	5	16.5	46	54	2.2	**68**	32	7.9	31	**69**	-12.3	36	64	-5.0
Mar	41	59	-2.5	46	54	0.1	46	54	2.0	55	45	3.4	**88**	13	6.8	**75**	25	7.6
Apr	39	61	-2.8	20	**80**	-9.7	38	63	-5.9	14	**86**	-12.5	40	60	-3.8	8	**92**	-9.7
May	63	38	6.6	65	35	4.6	29	**71**	-6.5	36	64	-2.6	38	63	-3.6	38	62	-4.4
Jun	29	**71**	-9.5	21	**79**	-11.6	58	42	5.7	59	41	5.1	33	**67**	-4.6	31	**69**	-4.9
Jul	43	57	-5.8	48	52	-1.2	58	42	4.6	59	41	5.6	25	**75**	-3.7	54	46	5.1
Aug	**85**	15	14.5	**76**	24	11.7	**100**	0	19.7	**100**	0	18.6	**88**	13	13.7	**77**	23	12.8
Sep	**89**	11	15.0	**88**	12	15.7	**100**	0	16.9	**95**	5	20.6	63	38	8.6	**83**	17	17.0
Oct	15	**85**	-16.4	17	**83**	-13.5	46	54	-3.6	50	50	-0.8	25	**75**	-11.4	33	**67**	-6.6
Nov	**92**	8	18.8	**98**	2	22.0	**96**	4	23.2	**100**	0	27.1	56	44	1.6	**85**	15	9.2
Dec	**83**	17	11.3	**97**	3	15.5	**92**	8	15.1	**100**	0	16.8	**88**	13	14.1	**100**	0	19.2
Spr	61	39	1.2	46	54	-0.8	33	**67**	-2.3	38	62	-1.6	53	47	1.6	30	**70**	-2.0
Sum	44	56	-2.0	44	56	-1.2	**79**	21	8.7	**86**	14	8.6	57	43	1.4	**83**	17	3.4
Aut	44	56	-2.0	55	45	1.3	**67**	33	2.6	**76**	24	5.4	33	**67**	-3.8	**73**	27	3.7
Win	**78**	22	7.4	**88**	12	9.8	59	41	10.7	**74**	26	14.5	58	42	8.5	**88**	13	19.7
SHY	50	50	-0.8	44	56	-0.9	**70**	30	3.6	**67**	33	4.0	46	54	0.2	64	36	1.2
WHY	59	41	2.9	**77**	23	5.9	57	43	6.5	**82**	18	10.8	50	50	3.0	**75**	25	12.1
Ann	40	60	-2.1	45	55	-0.6	62	38	3.1	**76**	24	5.7	33	**67**	-0.2	63	38	4.0

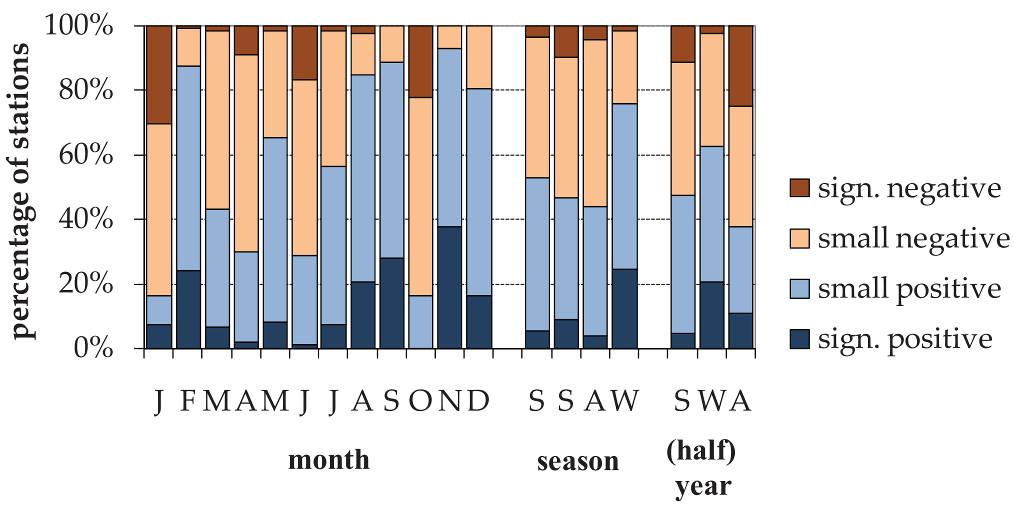


Figure 7.37: Percentage of significant positive and negative trends (Mann-Kendall test, $\alpha \leq 0.2$) for the Simple Daily Precipitation Intensity index (SDPI) for 1951—2000

2) Simple Daily Precipitation Index (SDPI): The SDPI that measures the average precipitation intensity on wet days, showed regional opposite annual trends, with distinct decreases in the North-eastern regions (ESH, EML and LAS) and increases in the South-western region TFM (Figure 7.35). Those regional trend patterns also emerge in the half year trends (Annex 27). Decreases in SDPI during the SHY were most often significant in region EML, while most stations within region TFM, show significant increasing Mann-Kendall trends during the WHY (Annex 25).

Compared to other indicators, the seasonal and half year trends are rather indifferent for most studied periods (Table 6.11, Annex 24), showing high spatial gradients (Annex 27). Regionally quite homogenous increases during all study periods were found for August, September, November and December (Table 6.11), while decreases in most periods occurred particularly frequent in January, April, June and October. Those are also the months with the highest percentage of significant positive or negative Mann-Kendall trends, respectively.

3) API-95P: Slight increases in the Average Precipitation Intensity on days above the 95th percentile were found in most months and seasons (Annex 24). This is true for all investigated periods and for both concepts of computing the 95th percentile described in section 2.3. The annual trend pattern of the

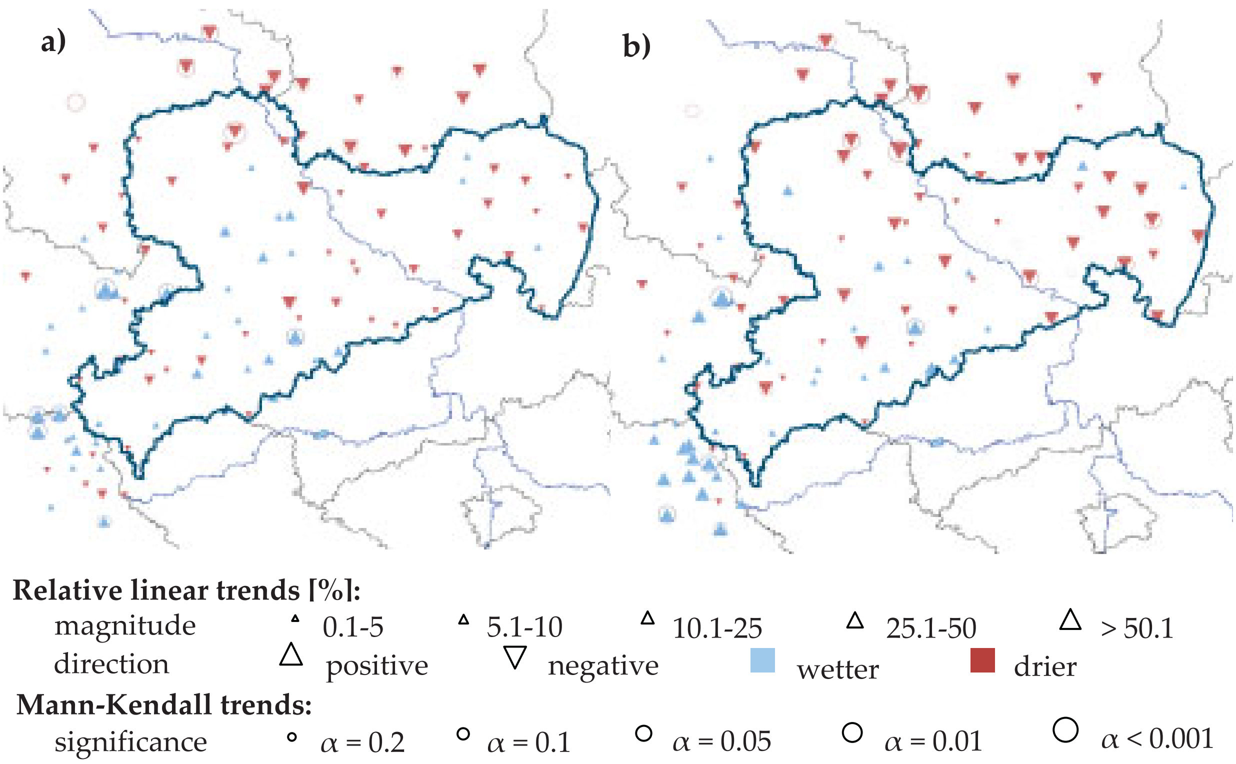


Figure 7.38: Map of the annual linear trends for a) the average precipitation intensity (API-95-ad) and b) the percentage of precipitation above normal precipitation at total precipitation (R-95P-ad) for the percentile calculation approach "ad"; 1951—2000

API-95P (Figure 7.38) are similar to those of the SDPI (Figure 7.35), although considerably more frequent negative monthly trends were observed for the API-95P (Annex 24, Annex 25). Annual decreases in API-95P from 1951 to 2000were mainly observed in the Northern parts of the study area (EML; Figure 7.38a, and Annex 26). Those spatial patterns are also reflected in the half year trends (Annex 27). Stations in region EML frequently show negative winter half year trends, despite predominantly positive winter half trends, as well as the highest negative summer half year trends. In contrast, the highest increases during the winter half year were observed in region TFM.

Quite independently from the total magnitude of the 95th percentile (the magnitude of the 95th percentile after the 'pd'-method is considerably higher than after the 'ad'-approach), the intensity of precipitation events above this threshold has increased at a high percentage of stations in March, September, November and December. The highest number of significant positive station trends for period 1951—2006 was observed in November and December (Annex 25), while January showed the highest percentage of significant negative trends. Decreases in the intensity of precipitation events above the 95th percentile as of 1951 were mainly observed in January and October, but those negative trends are not reflected in that extent in longer periods.

4) R-95P: The trends of the R-95P indicator (Percentage of precipitation above the 95th percentile on total precipitation) are very similar to those of the API-95P indicator with the highest percentages of positive trends in September, November and December (Annex 24). During those months, the trends are most frequently significant for period 1951—2000 (Annex 25). A considerable percentage of significant negative trends were only observed for January and October. Annually, the percentage of precipitation above the 95th percentile has decreased predominantly in the North (EML) and East (LAS) of the study area, whereas positive trends were frequently observed in the South-west (TFM; Figure 7.38b and Annex 26). In region TFM, the highest increases were observed for the winter half year (Annex 27)

7.3.2 Frequency of Heavy Precipitation Events

The annual frequency of daily precipitation totals above the absolute thresholds of 10 mm and 20 mm shows indifferent trends for 1950 to 2000. The trends of about half of the stations are positive and the other half negative (Table 7.12, Table 7.13). Decreases were observed at the majority of stations in the North and East of the study area, namely in the regions EML and LAS, whereas increases predominate in the south-western regions TFM and VTB (Figure 7.39). For longer time series as of 1941 or 1931, respectively, a majority of station trends indicates slight annual increases in the frequency of exceeding 10 or 20 mm daily precipitation.

In addition to the absolute thresholds of 10 and 20 mm daily precipitation, some relative thresholds were used to describe heavy precipitation events. Those are the 90th, the 95th and the 99th percentile. Two different calculation methods abbreviated with “ad” and “pd” were used for the calculation of

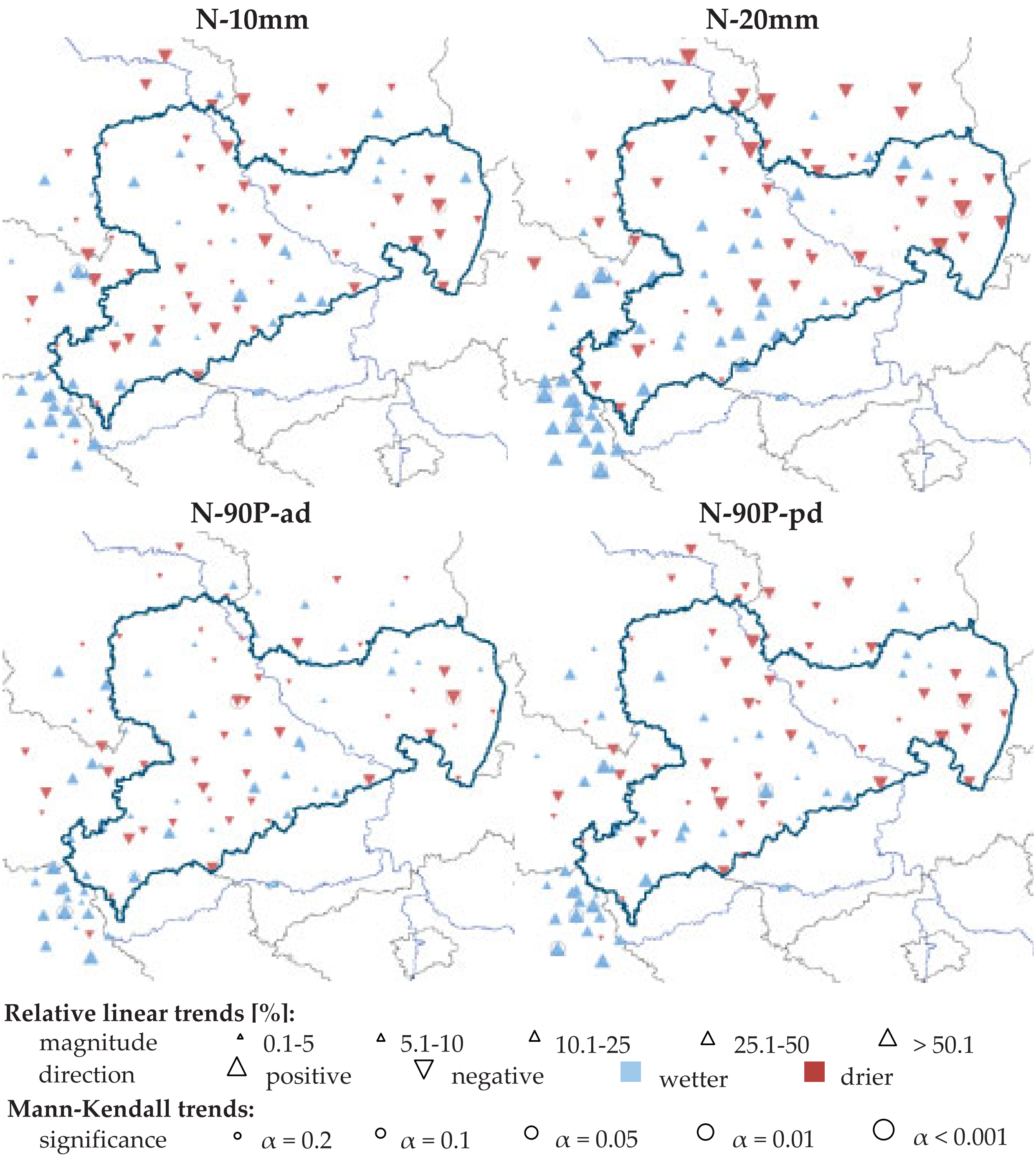


Figure 7.39: Map of the annual linear trends for the frequency of exceeding daily precipitation totals of 10 mm (N-10mm) and 20 mm (N-20mm) as well as the 90th percentile (N-90P) for approach “ad” and “pd” for 1951—2000 daily

percentiles (for details regarding the percentile calculation please see section 2.3). Generally, the percentiles of the "pd"-approach are considerably higher than those of the "ad"-approach, as only days with precipitation ($R_d \geq 0.1$ mm) are included in the computation of percentiles.

The annual results for changes in the frequency of heavy precipitation events are quite similar for the absolute and relative thresholds (Table 7.12 to Table 7.15; Annex 24). As already described for the absolute threshold, increasing station trends predominate in the South-West and negative trends in the North and East (Figure 7.39; Annex 26). This is particularly true for the higher thresholds and thus more extreme daily precipitation events.

The observed indifferent trends in the annual frequency of heavy precipitation events match the general precipitation trends (sub-section 7.1.1) and are due to different seasonal developments. With decreasing precipitation totals during

Table 7.12: Average linear trends (Ø) and percentage of positive (+) and negative (-) station trends of the frequency of daily precipitation events above 10 mm (N-10mm) for individual periods (blue/ orange: trends towards more/ less (extreme/ frequent) precipitation; bold: percentages of station trends > 66.67%)

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	38	63	-27.8	51	49	-9.2	54	46	3.4	64	36	15.5	31	**69**	-24.5	58	42	11.3
Feb	57	43	11.6	**75**	25	35.4	33	**67**	-44.1	45	55	-18.6	13	**88**	-83.6	36	64	-47.0
Mar	**80**	20	29.6	**89**	11	33.3	**75**	25	29.4	**91**	9	40.6	**81**	19	39.7	**83**	17	39.4
Apr	31	**69**	-13.5	13	**87**	-35.5	21	**79**	-23.2	5	**95**	-49.6	33	**67**	-11.3	8	**92**	-41.6
May	36	64	-13.0	45	55	-5.3	25	**75**	-18.2	45	55	-9.4	25	**75**	-8.8	46	54	-4.0
Jun	15	**85**	-30.9	5	**95**	-37.6	58	42	-2.1	27	**73**	-9.8	47	53	-3.5	15	**85**	-10.6
Jul	31	**69**	-17.0	37	63	-8.5	54	46	-0.8	41	59	-3.5	38	63	-9.8	46	54	-1.7
Aug	**68**	32	13.6	66	34	8.7	**88**	13	21.3	**91**	9	20.1	63	38	1.1	46	54	0.1
Sep	**77**	23	25.3	**77**	23	21.4	**96**	4	37.9	**91**	9	38.0	**94**	6	33.1	**83**	17	37.0
Oct	16	**84**	-42.6	12	**88**	-46.1	50	50	-10.3	50	50	-14.8	19	**81**	-38.5	25	**75**	-38.2
Nov	**89**	11	51.0	**100**	0	71.2	**92**	8	54.6	**100**	0	78.8	**88**	13	22.3	**100**	0	56.0
Dec	**88**	13	41.1	**88**	12	42.6	**96**	4	49.9	**100**	0	53.0	**100**	0	73.7	**100**	0	80.2
Spr	47	53	-1.6	41	59	-3.7	25	**75**	-6.5	38	62	-6.0	53	47	4.4	40	60	-2.5
Sum	29	**71**	-11.4	27	**73**	-11.9	63	38	6.0	50	50	2.0	36	64	-2.2	42	58	-3.0
Aut	61	39	9.8	**75**	25	14.5	**79**	21	25.5	**81**	19	29.4	47	53	5.2	**73**	27	16.9
Win	**72**	28	19.6	**85**	15	28.8	**73**	27	17.2	**84**	16	28.6	**67**	33	19.4	**88**	13	47.2
SHY	31	**69**	-6.8	25	**75**	-8.6	**70**	30	4.3	57	43	1.0	38	62	-0.3	27	**73**	-2.3
WHY	**72**	28	14.0	**83**	17	21.6	**71**	29	22.7	**88**	12	35.5	50	50	11.4	**88**	13	35.4
Ann	49	51	-0.5	60	40	1.9	**67**	33	9.5	**76**	24	12.4	50	50	2.9	**75**	25	10.8

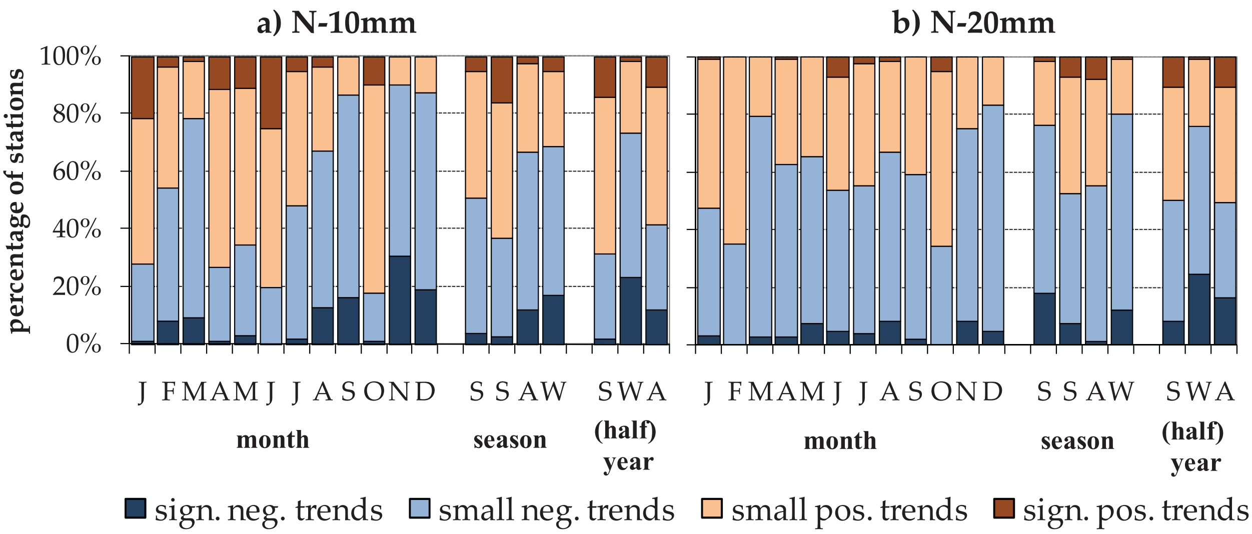


Figure 7.40: Percentage of significant positive and negative trends (Mann-Kendall trend test, $\alpha \leq 0.2$) for the frequency of exceeding a) 10 mm (N-10mm) and b) 20 mm (N-20mm) daily precipitation for 1951—2000

Table 7.13: Average linear trends (Ø) and percentage of positive (+) and negative (-) station trends of the frequency of daily precipitation events above 20 mm (N-20mm) for individual periods (blue/ orange: trends towards more/ less (extreme/ frequent) precipitation; bold: percentages of station trends > 66.67%)

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	48	52	8.5	55	45	22.6	**67**	33	64.0	**73**	27	118	**69**	31	36.8	**75**	25	123
Feb	35	65	-43.2	44	56	-28.2	42	58	-28.2	50	50	-9.6	19	**81**	-140	45	55	-52.3
Mar	**79**	21	107	**70**	30	59.3	**92**	8	113	**82**	18	71.5	**69**	31	107	58	42	27.4
Apr	65	35	28.2	43	57	-6.8	63	38	35.9	52	48	-2.8	60	40	45.2	42	58	21.7
May	63	38	20.6	56	44	6.3	42	58	-0.8	45	55	-2.1	56	44	9.0	54	46	4.4
Jun	46	54	-12.0	25	**75**	-36.6	**88**	13	32.3	59	41	8.8	**67**	33	7.1	46	54	-12.1
Jul	26	**74**	-35.7	37	63	-17.7	46	54	5.4	45	55	3.8	38	63	-11.0	38	62	-0.1
Aug	**69**	31	21.6	**79**	21	24.1	**88**	13	35.5	**82**	18	51.1	**69**	31	18.3	**69**	31	33.1
Sep	51	49	-10.0	55	45	-4.3	**67**	33	49.3	**82**	18	54.1	56	44	36.8	**67**	33	59.9
Oct	16	**84**	-70.7	17	**83**	-83.6	54	46	8.9	55	45	-6.7	31	**69**	-61.3	42	58	-45.2
Nov	**79**	21	66.9	**85**	15	102	**79**	21	74.8	**90**	10	102	31	**69**	-39.2	46	54	-5.4
Dec	**86**	14	123	**91**	9	117	**83**	17	58.0	**76**	24	65.9	63	38	65.0	**75**	25	103
Spr	**79**	21	35.7	58	42	8.4	**75**	25	29.2	52	48	12.7	**80**	20	31.5	50	50	0.8
Sum	32	**68**	-10.0	35	65	-8.6	**88**	13	23.6	**86**	14	22.2	64	36	4.7	**67**	33	6.9
Aut	43	57	-15.7	52	48	-5.7	**75**	25	42.1	**71**	29	46.8	40	60	-11.6	64	36	19.4
Win	**83**	17	72.4	**79**	21	79.6	**68**	32	48.1	**89**	11	81.0	**75**	25	60.6	**100**	0	112
SHY	48	52	-1.7	41	59	-4.8	**91**	9	22.9	**81**	19	22.2	**77**	23	10.5	**82**	18	12.5
WHY	**71**	29	24.0	**74**	26	25.9	**71**	29	49.7	**88**	12	65.7	58	42	11.5	**88**	13	48.0
Ann	51	49	3.1	50	50	2.7	**81**	19	30.3	**76**	24	9.0	58	42	8.4	**75**	25	23.9

the summer half year there exists a tendency to a declining frequency of exceeding the absolute as well as the relative thresholds (Table 7.12 to Table 7.15, Annex 27). This is particularly true for the time series starting in 1951. For longer periods as of 1941 or 1931, increases in the frequency of exceeding 20 mm daily precipitation were observed at the majority of stations.

Matching the general winterly precipitation increases, the winter half year trends of heavy precipitation event frequency are positive at a majority of stations for most periods (Table 7.12 to Table 7.15, Annex 27). Significant, according to the Mann-Kendall trend test, are those increases at about 20% to 40% of all stations for all investigated thresholds (Figure 7.40, Figure 7.41, Annex 25). The highest percentage of statistically significant positive winter half year trends was observed for the smallest threshold namely the 90^{th} percentile with calculation approach "ad". Generally less stations show significant negative summer half year trends than significant positive winter half year trends.

The frequency of heavy precipitation events monthly trends were calculated, additionally to seasonal and annual trend analysis. For the interpretation of monthly trends it is important to consider than the monthly analysis of extreme precipitation events is less reliable for the highest thresholds of 20 mm and the 99^{th} percentile compared to medium extreme events (thresholds: 10 mm, 90^{th} and 95^{th} percentile). Due to the rarity of such extremes the trends are highly influenced by random events and outliers.

The summerly decreases in heavy precipitation frequency are most pronounced during the months April to July for all investigated periods (Table 7.12; Annex 24), particularly for the lower thresholds of 10 mm and the 90^{th} percentile. Those are also the months with the highest decreases in precipitation totals (sub-section 7.1.1). Matching the negative general precipitation trends, decreases in the frequency of heavy precipitation events were also observed at a high percentage of stations during October. Regionally quite homogenous increases in the frequency of heavy precipitation events occurred during March, August, November and December during most investigated periods.

Opposite developments in the frequency of heavy precipitation events in comparison to the general precipitation trends are possible in particular for the most extreme precipitation events (highest thresholds). In the months April to June, for example, the frequency of exceeding 20 mm daily rainfall or the 99^{th} percentile has increased at a high percentage of stations (Table 7.12; Annex 24), despite pronounced decreases in precipitation totals. The simultaneously observed increases in the frequency of dry periods in May and June indicate that the precipitation in those months got extremer at both tails of the precipitation

Table 7.14: Average linear trends (Ø) and percentage of positive (+) and negative (-) station trends of the frequency of daily precipitation events above the 90th percentile (N-90P-ad) for individual periods (blue/ orange: trends towards more/ less (extreme/ frequent) precipitation; bold: percentages of station trends > 66.67%)

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	50	50	0.5	62	38	7.5	58	42	13.0	**68**	32	21.2	38	63	-3.3	**75**	25	13.4
Feb	**93**	7	36.0	**93**	7	40.9	46	54	-3.5	**73**	27	10.4	19	**81**	-14.8	45	55	-0.2
Mar	**99**	1	39.9	**98**	2	39.9	**96**	4	42.4	**91**	9	43.4	**88**	13	30.8	**75**	25	33.3
Apr	13	**88**	-27.9	4	**96**	-39.7	17	**83**	-24.0	10	**90**	-34.9	20	**80**	-22.2	8	**92**	-38.9
May	19	**81**	-19.5	28	**72**	-9.6	8	**92**	-32.5	14	**86**	-18.9	13	**88**	-27.2	15	**85**	-18.4
Jun	18	**82**	-25.5	6	**94**	-29.7	58	42	0.9	32	**68**	-5.3	33	**67**	0.0	23	**77**	-6.9
Jul	37	63	-10.2	33	**67**	-7.6	46	54	0.6	41	59	-3.2	31	**69**	-6.6	38	62	-3.6
Aug	**68**	32	12.3	66	34	8.2	**88**	13	19.0	**82**	18	14.9	38	63	-1.6	38	62	-3.3
Sep	**80**	20	14.3	**88**	12	17.7	**92**	8	21.7	**95**	5	27.0	**94**	6	18.7	**100**	0	27.8
Oct	20	**80**	-15.6	38	62	-4.7	29	**71**	-10.8	45	55	-2.5	13	**88**	-38.4	8	**92**	-22.8
Nov	**89**	11	32.5	**100**	0	46.2	**83**	17	26.4	**100**	0	42.2	**81**	19	19.3	**92**	8	35.3
Dec	**82**	18	17.6	**83**	17	15.4	**100**	0	38.5	**90**	10	34.9	**100**	0	53.1	**100**	0	53.2
Spr	42	58	-5.5	39	61	-4.4	25	**75**	-9.8	33	**67**	-7.1	20	**80**	-9.6	20	**80**	-11.8
Sum	33	**67**	-9.0	23	**77**	-10.0	**71**	29	7.2	**68**	32	2.8	36	64	-2.0	25	**75**	-3.4
Aut	**71**	29	9.7	**92**	8	18.0	**71**	29	13.0	**95**	5	20.5	47	53	1.2	**91**	9	15.3
Win	**82**	18	18.6	**90**	10	21.5	**77**	23	17.4	**84**	16	23.8	**75**	25	17.5	**88**	13	32.6
SHY	23	**77**	-7.2	22	**78**	-8.2	35	65	-1.2	38	62	-3.5	31	**69**	-5.5	18	**82**	-7.0
WHY	**89**	11	18.7	**95**	5	22.9	**86**	14	21.3	**88**	12	28.7	58	42	12.0	**88**	13	26.7
Ann	54	46	1.3	66	34	4.1	**67**	33	5.9	65	35	7.7	33	**67**	-0.6	63	38	4.6

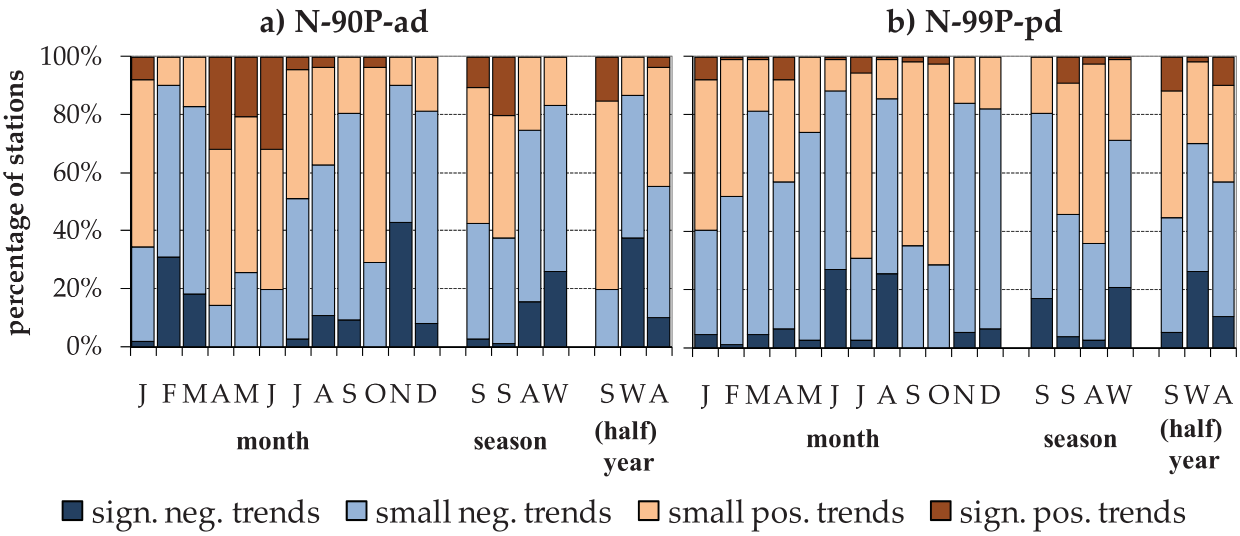


Figure 7.41: Percentage of significant positive and negative trends (Mann-Kendall trend test, $\alpha \leq 0.2$) for the frequency of daily precipitation events above a) the 90th percentile (N-90P-ad) and b) the 99th percentile (N-99P-pd) for 1951—2000

Table 7.15: Average linear trends (Ø) and percentage of positive (+) and negative (-) station trends of the frequency of daily precipitation events above the 99th percentile (N-99P-pd) for individual periods (blue/ orange: trends towards more/ less (extreme/ frequent) precipitation; bold: percentages of station trends > 66.67%)

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	37	63	-26.2	48	52	6.5	58	42	39.4	**68**	32	86.6	44	56	-13.8	58	42	63.5
Feb	50	50	-9.3	65	35	21.6	46	54	-20.0	50	50	3.3	13	**88**	-126	36	64	-59.3
Mar	**85**	15	80.1	**72**	28	40.7	**96**	4	106	**86**	14	75.9	**81**	19	96.5	**67**	33	74.2
Apr	**67**	33	52.8	52	48	9.4	**67**	33	44.8	38	62	0.6	47	53	48.6	33	**67**	-3.4
May	**70**	30	56.6	58	42	22.1	42	58	-9.0	41	59	-27.5	63	38	24.6	54	46	3.7
Jun	59	41	18.5	45	55	-18.8	**83**	17	75.1	**77**	23	53.4	**67**	33	20.6	54	46	2.7
Jul	16	**84**	-78.0	28	**72**	-49.3	54	46	8.2	59	41	12.1	31	**69**	-13.7	31	**69**	-1.2
Aug	51	49	6.4	53	47	21.9	63	38	59.8	59	41	64.7	**81**	19	85.3	**69**	31	97.4
Sep	32	**68**	-38.8	43	57	-18.8	50	50	18.8	**68**	32	63.2	44	56	-21.4	58	42	31.4
Oct	20	**80**	-82.5	21	**79**	-90.6	58	42	11.0	55	45	7.6	31	**69**	-58.9	42	58	-11.4
Nov	**85**	15	87.3	**89**	11	116	**92**	8	93.6	**90**	10	128	19	**81**	-52.1	46	54	1.4
Dec	**83**	17	87.8	**85**	15	88.9	63	38	47.9	62	38	30.8	**81**	19	30.6	**75**	25	38.5
Spr	**87**	13	58.2	**72**	28	22.1	**67**	33	45.0	62	38	19.1	**73**	27	55.1	50	50	14.5
Sum	33	**67**	-33.1	30	**70**	-22.0	63	38	25.0	64	36	25.7	57	43	11.0	50	50	20.6
Aut	37	63	-26.7	47	53	-10.2	58	42	33.5	62	38	55.1	33	**67**	-49.1	55	45	5.7
Win	**73**	27	49.7	**81**	19	64.3	59	41	31.4	**68**	32	58.9	58	42	4.6	**100**	0	85.3
SHY	46	54	-13.4	42	58	-9.6	65	35	10.1	57	43	14.6	46	54	-3.0	55	45	10.4
WHY	64	36	23.4	**67**	33	27.0	**67**	33	42.2	**76**	24	63.7	50	50	-2.4	**75**	25	45.3
Ann	51	49	2.6	53	47	5.2	**86**	14	36.9	**88**	12	47.4	58	42	7.5	**75**	25	23.8

distribution. In contrast, the general precipitation increases in February are not reflected in an increasing frequency of extreme heavy precipitation events.

The highest percentages of significant positive Mann-Kendall trends in 1951—2000 were observed in February, March, November and December for the frequency of medium extreme precipitation events (thresholds: 90th and 95th percentile), and in June and August for the most extreme events (threshold: 99th percentile, "pd"-approach; Figure 7.41; Annex 25). Significant decreases in the frequency of heavy precipitation events were observed most frequently in February and April to June for the lower thresholds. Generally, significant monthly changes were less frequently observed for the higher thresholds than compared to the lower ones.

7.3.3 Magnitude of Heavy Precipitation Events

The magnitude of heavy precipitation events shows similar to their frequency quite indifferent annual trends (Figure 7.42; Table 7.16; Table 7.17; Annex 24), if percentile thresholds are used. Nevertheless, positive trends were calculated for a slightly higher percentage of stations for most periods. For the period 1951—2000, frequent decreases in the annual magnitude of the 95th and 99th percentile were observed in the north-eastern regions LAS and TFM, whereas the south-western regions TFM and VTB are characterised by pronounced increases. Analysing the highest precipitation events per month and season delivers partly opposite results compared to the percentile magnitudes for 1951—2000, with pronounced decreases in the maximum precipitation total for one, three and five days (Figure 7.42; Annex 24) in almost all regions. For other periods, the results are regionally not as homogenous as for this period.

Seasonally different developments occurred with predominantly increasing percentile magnitudes during the winter half year and opposite trends during the summer half year (Table 7.16; Table 7.17; Annex 27). Summerly decreases least frequently occurred for the highest percentile (99P), and for longer periods starting in 1941 or 1931, even increases predominate. For 1951—2000, the decreases in magnitude of the 99th percentile were most pronounced in the north-eastern regions LAS and EML, while in the Southern regions positive trends occurred more frequently. The percentage of positive winter half year trends is decreasing with the magnitude of the percentile threshold; for the 90th percentile almost all stations showed positive trends whereas for the 99th percentile about 25% of the stations trends indicate decreases in percentile magnitude. Statistically significant are the increases during the winter half year for period 1951—2000 at 25 to 40% of the stations, mainly situated in the South-west of the study area. (Figure 7.43; Annex 25, Annex 27). Less of the negative summer half year trends are significant according to the Mann-Kendall trend test.

The monthly trends of percentile magnitude are spatially and temporally most homogenous during March, September, November and December, showing increases in the magnitude of all percentile thresholds (Table 7.16, Table 7.17; Annex 24). Those are also the months with the highest percentages of statistically significant positive Mann-Kendall trends (Figure 7.43; Annex 25). Decreases in the magnitude of the 90th and 95th percentile were primarily observed in the months April to July and October for all investigated time intervals. In contrast negative trends have been calculated less frequently for those months for the 99th percentile. Those results are also reflected partly in the significance of the Mann-Kendall trends, with high percentages of significant negative trends (20 to 40% of all station trends) in April, May and June for the magnitude of the 90th and 99th percentile. For August and October, only a small percentage of the decreasing trends are statistically significant. Few significant negative monthly trends were calculated for the 99th percentile, its magnitude significantly decreased during 1951—2000 only in January.

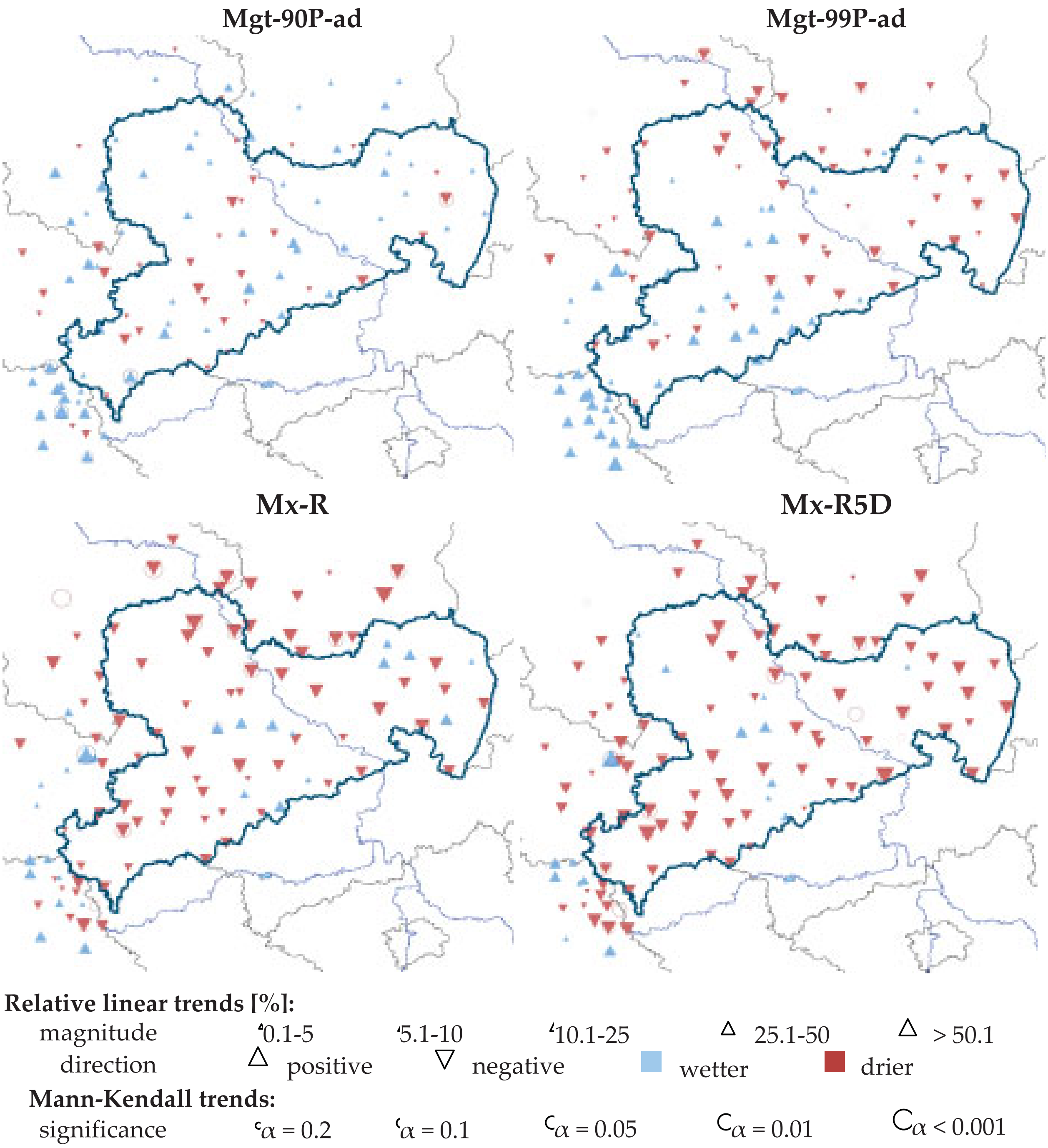


Figure 7.42: Annual trend map for the magnitude of the 90th (Mgt-90P-ad) and the 99th percentile (Mgt-99P-ad) of daily precipitation totals, the maximum daily precipitation total (Mx-R) and the highest 5-day precipitation total (Mx-R5D) for 1951—2000

Table 7.16: Average linear trends (Ø) and percentage of positive (+) and negative (-) station trends of the magnitude of the 90th percentile (Mgt-90P-ad) of daily precipitation for individual periods (blue/ orange: trends towards more/ less (extreme/ frequent) precipitation; bold: percentages of station trends > 66.67)

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	45	55	-3.3	55	45	2.4	54	46	0.6	**68**	32	5.5	19	**81**	-11.5	50	50	-2.0
Feb	**94**	6	22.0	**97**	3	26.0	33	**67**	-7.4	45	55	2.1	19	**81**	-20.7	36	64	-5.7
Mar	**89**	11	22.3	**96**	4	23.3	**96**	4	25.6	**100**	0	27.7	**100**	0	21.7	**100**	0	25.6
Apr	13	**87**	-20.0	5	**95**	-28.5	8	**92**	-18.7	5	**95**	-25.9	27	**73**	-11.5	8	**92**	-20.1
May	23	**77**	-15.1	36	64	-5.9	8	**92**	-24.7	14	**86**	-13.0	6	**94**	-17.9	31	**69**	-7.5
Jun	17	**83**	-19.9	7	**93**	-23.4	54	46	-4.0	36	64	-9.3	40	60	-0.3	31	**69**	-4.9
Jul	19	**81**	-24.4	14	**86**	-19.2	42	58	-5.2	14	**86**	-9.9	19	**81**	-12.4	23	**77**	-11.0
Aug	**68**	32	9.6	**70**	30	10.8	**92**	8	17.2	**95**	5	21.1	44	56	-0.4	62	38	4.1
Sep	**82**	18	12.6	**83**	17	12.9	**96**	4	23.2	**100**	0	24.8	**94**	6	20.8	**92**	8	25.1
Oct	18	**82**	-19.4	18	**82**	-15.6	54	46	-1.9	50	50	-0.6	19	**81**	-29.2	17	**83**	-20.5
Nov	**95**	5	33.3	**100**	0	40.6	**100**	0	25.5	**100**	0	34.6	**94**	6	19.3	**100**	0	31.7
Dec	**87**	13	15.9	**76**	24	8.1	**92**	8	25.6	**90**	10	18.3	**100**	0	37.1	**100**	0	32.5
Spr	38	63	-4.0	35	65	-3.6	21	**79**	-5.6	24	**76**	-4.6	40	60	-3.9	20	**80**	-5.8
Sum	26	**74**	-10.2	18	**82**	-10.6	54	46	2.4	59	41	-0.6	36	64	-5.0	25	**75**	-6.1
Aut	**80**	20	12.4	**92**	8	16.5	**88**	13	13.9	**95**	5	17.6	40	60	1.5	**82**	18	10.2
Win	**87**	13	12.3	**90**	10	13.9	**68**	32	9.5	**74**	26	13.1	**75**	25	12.5	**88**	13	22.3
SHY	25	**75**	-5.6	20	**80**	-6.6	39	61	-1.5	24	**76**	-3.2	15	**85**	-4.6	18	**82**	-5.5
WHY	**94**	6	14.5	**97**	3	17.8	**81**	19	16.2	**88**	12	22.3	58	42	10.1	**88**	13	21.8
Ann	64	36	2.3	**74**	26	3.9	**71**	29	5.4	**82**	18	7.4	50	50	1.0	63	38	4.9

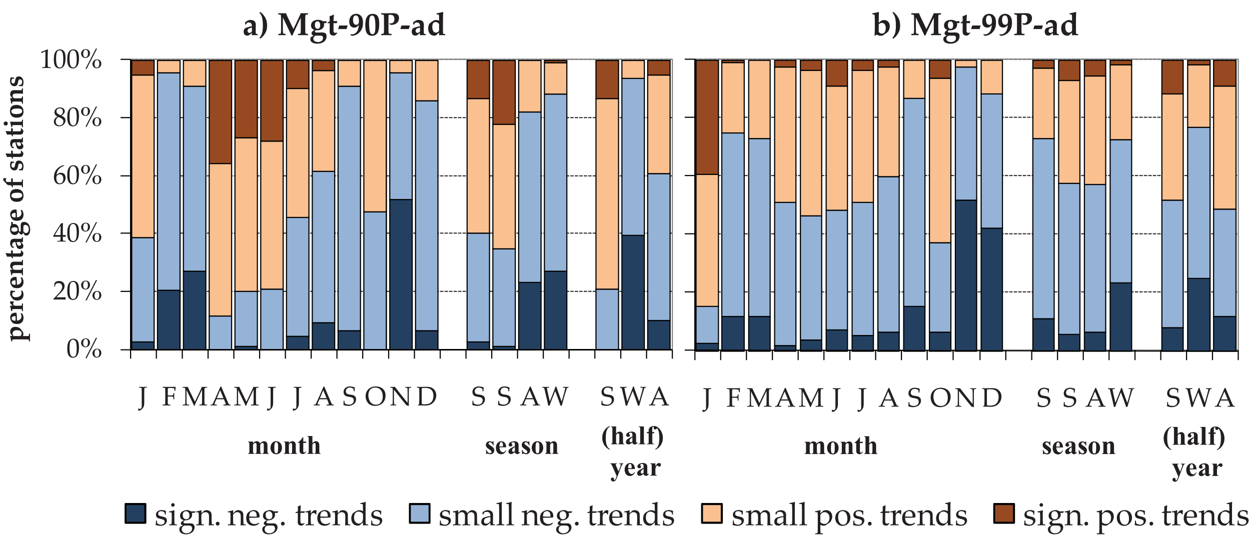


Figure 7.43: Percentage of significant positive and negative trends (Mann-Kendall trend test, $\alpha \leq 0.2$) for the magnitude of the a) 90th percentile (Mgt-90P-ad) and b) 99th percentile (Mgt-99P-ad) for 1951—2000

Table 7.17: Average linear trends (Ø) and percentage of positive (+) and negative (-) station trends of the magnitude of the 99th percentile (Mgt-99P-ad) of daily precipitation for individual periods (blue/ orange: trends towards more/ less (extreme/ frequent) precipitation; bold: percentages of station trends > 66.67)

	1951-2000			1951-2006			1941-2000			1941-2006			1931-2000			1931-2006		
	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø	+	-	Ø
Jan	17	**83**	-19.4	32	68	-6.4	54	46	-5.2	59	41	11.9	25	**75**	-18.0	50	50	3.1
Feb	**73**	27	9.6	**86**	14	16.1	46	54	-9.3	45	55	-2.0	13	**88**	-34.0	18	**82**	-20.1
Mar	**83**	17	16.0	**83**	17	12.3	**88**	13	20.1	**86**	14	16.4	**88**	13	18.7	**75**	25	15.4
Apr	55	45	4.3	29	**71**	-8.1	50	50	1.0	29	**71**	-10.6	60	40	5.2	33	**67**	-9.5
May	55	45	3.4	49	51	0.8	33	**67**	-9.0	36	64	-9.6	38	63	-3.7	46	54	-3.6
Jun	49	51	-1.3	27	**73**	-11.6	**75**	25	12.1	**68**	32	3.9	60	40	1.6	46	54	-4.4
Jul	31	**69**	-15.3	40	60	-5.8	58	42	1.4	64	36	5.6	19	**81**	-12.1	46	54	-1.9
Aug	63	37	6.1	**69**	31	10.6	**92**	8	19.4	**82**	18	22.7	**81**	19	15.4	**77**	23	21.4
Sep	54	46	0.7	64	36	5.5	**92**	8	17.7	**82**	18	27.2	50	50	5.2	**67**	33	19.5
Oct	25	**75**	-13.5	22	**78**	-13.8	63	38	14.1	59	41	14.6	31	**69**	-15.3	42	58	-8.6
Nov	**96**	4	27.6	**98**	2	32.0	**100**	0	32.5	**100**	0	38.9	38	63	0.8	**77**	23	13.6
Dec	**96**	4	27.0	**99**	1	29.1	**96**	4	27.5	**100**	0	30.1	**100**	0	29.4	**100**	0	37.6
Spr	**84**	16	10.6	65	35	3.0	63	38	6.9	57	43	2.5	60	40	8.9	30	**70**	0.0
Sum	44	56	-5.7	50	50	-2.4	**75**	25	11.2	**82**	18	12.7	**71**	29	4.2	**83**	17	8.3
Aut	42	58	-2.6	49	51	0.7	**75**	25	11.4	**71**	29	14.8	33	**67**	-7.9	55	45	4.4
Win	**68**	32	9.1	**87**	13	13.4	**73**	27	14.2	**89**	11	20.4	42	58	5.8	**88**	13	21.6
SHY	42	58	-3.3	41	59	-3.5	**83**	17	8.7	**76**	24	8.7	**77**	23	2.9	**73**	27	5.1
WHY	**73**	27	7.1	**80**	20	9.6	57	43	10.7	**71**	29	16.5	42	58	-2.0	63	38	10.5
Ann	49	51	-0.1	43	57	-0.2	**90**	10	11.4	**88**	12	12.8	58	42	1.3	**75**	25	6.9

In contrast to the already described differences in the annual trends, the seasonal and monthly trend pattern of maximum daily, 3-day and 5-day precipitation are quite similar to those of the percentile thresholds (Annex 24, Annex 25 and Annex 27). They also indicate increases in the magnitude of heavy precipitation events during the winter half year. Those increases are most pronounced during March, November and December, showing high percentages of significant Mann-Kendall trends (Annex 25). In contrast, the summer half year is characterised by decreases in the magnitude of heavy precipitation events, true for a high percentage of stations. But those decreases are less frequently significant than the increases in November and December. Similarly to the magnitude of the 99th percentile the maximum daily, 3-day and 5-day precipitation for 1951—2000 decreased most significantly during January.

7.3.4 Spatiotemporal trend characteristics of heavy precipitation indicators

Spatiotemporal trend characteristics of 'Heavy Precipitation Indicators' (HPI) were analysed using a moving 30-year-trend analysis starting with period

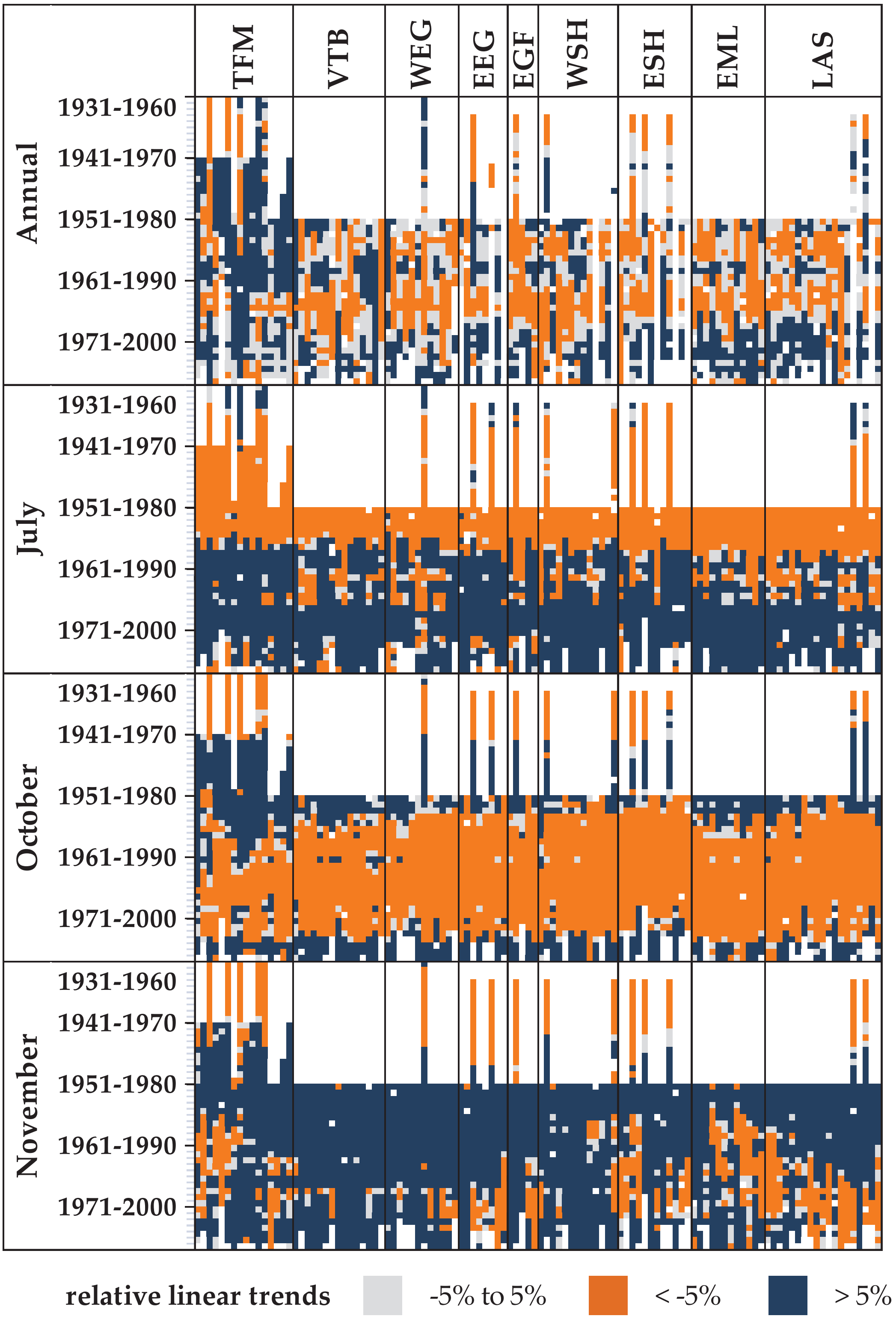


Figure 7.44: Moving 30-year-trends (relative linear trends) of the exceedance frequency of the 90th percentile calculated with approach "ad" for the annual time series and the months July, October and November for the periods 1901—1930 to 1977—2006

1931—1960 and shifting the period by one year until 1977—2006. Analysis results are discussed exemplary for two indicators, as the trend characteristics of individual HPI are very similar and mainly depend on the magnitude of the

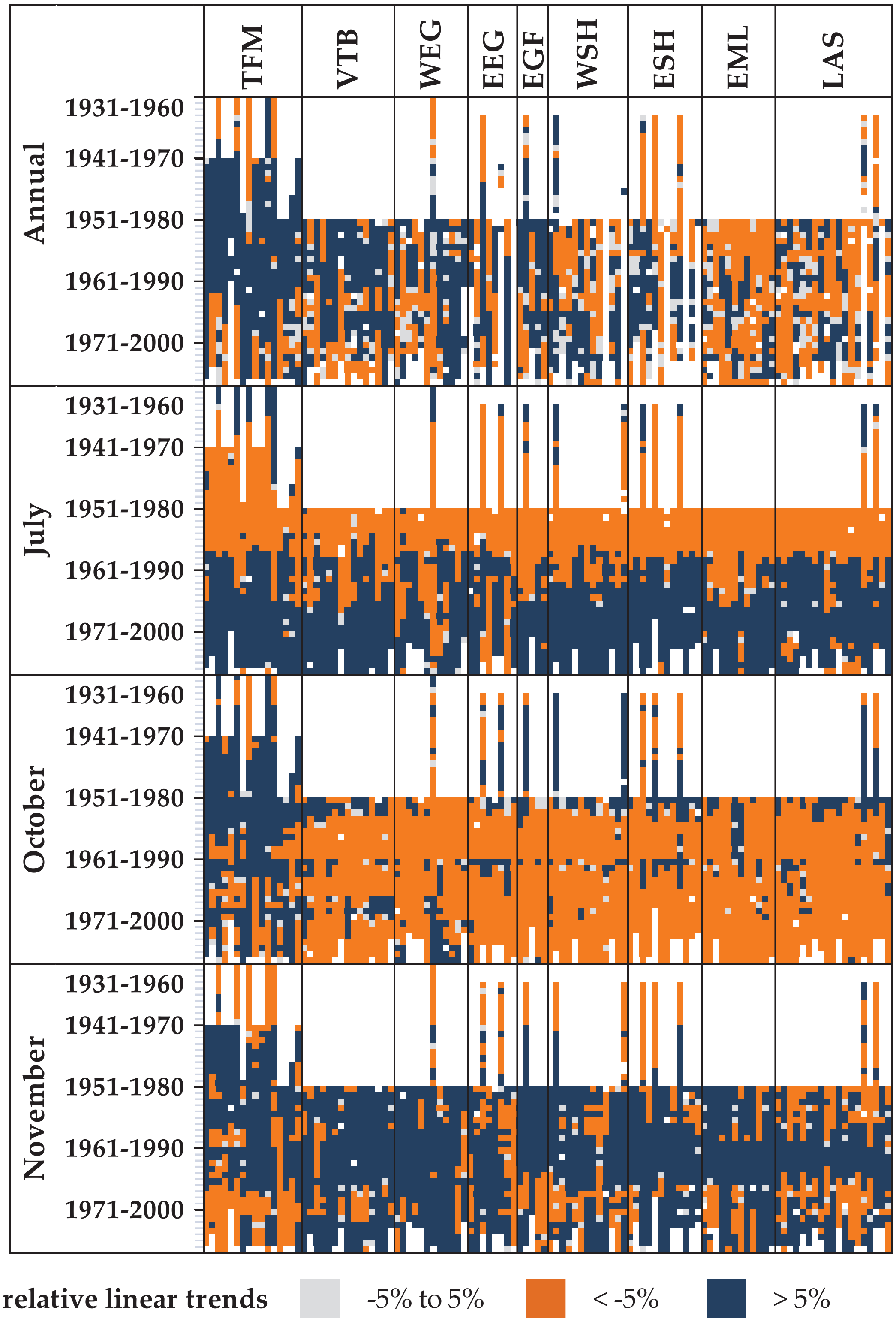


Figure 7.45: Moving 30-year-trends (relative linear trends) of the exceedance frequency of the 99th percentile calculated with approach "ad" for the annual time series and the months July, October and November for the periods 1901—1930 to 1977—2006

threshold and thus the rarity of the events. Those indices are the frequency of exceeding the 90th percentile (N-90P), exemplary for moderately extreme HPI (Figure 7.44; Annex 28), and the frequency of exceeding the 99th percentile (N-99P), exemplary for more extreme HPI (Figure 7.45; Annex 29). Both percentile thresholds were calculated using the approach "ad". Annually and seasonally, the 30-year trends are quite variable in time and space, while for some months, like February, July, October, November and December, more regionally homogenous developments occurred. Nevertheless, a high influence of large-scale circulation pattern on 30-year HPI trends is also visible in the seasonal HPI time series, with a high percentage of trends of same sign within most regions, at least during some periods.

Generally, the HPI trend patterns of the summer half year are more similar to the annual ones than those of the winter half year, particularly for moderate extremes (e.g., N-90P; Annex 28). Furthermore, the regional differentiation of trends is higher for the more extreme threshold of the 99th percentile (Annex 29). Several sign reversals in the annual and half year 30-year trends of the indicator N-90P occurred simultaneously in most regions (except for region TFM), while negative trends are more persistent in the regions WSH, EML and LAS for the indicator N-99P.

In spring many of the 30-year trends for the 90th percentile are negative (Annex 28), while positive short-term trends are more frequent for the 99th percentile in the regions TFM, VTB, WSH and the Erzgebirge regions (WEG, EEG and EGF), particularly between 1951—1980 and 1965—1994 (Annex 29). A reversal from negative 30-year trends around 1951—1980 to positive ones at the end of the study period occurred for both percentile thresholds in summer. Autumn is characterised by a band of negative 30-year trends for the indicator N-90P around 1965—1994. This band of negative trends is particularly expanded within the regions ESH, EML and LAS. Negative, but not very persistent autumn trends predominate in most regions for the N-99P-indicator. Although positive 30-year trends dominate the winter season for both percentile thresholds, they occur more frequently for the higher threshold.

February (Annex 28) and July (Figure 7.44) are characterised by a trend reversal from negative to positive trends for the frequency of exceeding the 90th percentile at about 1955—1984, while for the 99th percentile such a distinct trend reversal in all regions has only been observed in July (Figure 7.45) but not in February (Annex 29). Highly persistent negative 30-year trends during most of the study period occurred in April, May, June and October for the 90th percentile (Figure 7.44; Annex 28). For more extreme heavy precipitation events (N-99P), the short-term trend pattern of April, May and June are temporarily and spatially very heterogeneous (Annex 29), just the October pattern is similar to the one of the N-90P indicator (Figure 7.45), except for more frequent increasing trends in region TFM. Quite similar for both percentile thresholds are also the trend pattern of November (Figure 7.44, Figure 7.45) and December (Annex 28, Annex 29). In those months comparatively persistent trends toward more frequent heavy precipitation events exist throughout the entire study period.

Comparing the short-term trends of differently extreme heavy precipitation indices reveals that the trends of more extreme HPI are temporarily and spatially more variable and instable than those of moderately extreme HPI. Single accidental occurrences or outliers very strongly influence the trends, in particular for such short time scales like 30 years. Those analyses confirm that the trends of moderately extreme events are generally more robust than those of the more extreme events.

7.3.5 Duration of Wet Periods

The average duration of decile wet periods declined from the first to the second half of the 20th century within most regions (Figure 7.46). Only within the regions EML (Elbe-Mulde Lowlands), LAS (Lausitz and Spreewald) and TFM (Thuringian-Franconian Mountains), the average wet period duration is of almost same size for periods 1901—1950 and 1951—2000. In almost all regions, only very slight changes in the average wet period duration occurred within the second half of the 20th century. For the regions TFM and LAS, the wet period duration of 1976—2000 was considerably higher than the one within 1951—1975.

Despite decreases in average decile wet period duration (Figure 7.46), the longest events were frequently observed during the second part of the 20th century (Figure 7.46). Those increases in maximum wet period duration from 1901—1950 to 1951—2000 predominantly occurred in the regions with just small changes in mean wet period duration, namely TFM, EML and LAS. In the other regions, small changes or decreases in maximum wet period duration were observed. The shortest maximum wet periods were observed from 1951 to 1975 in a majority of regions. Exceptions are the regions TFM, WSH and LAS with the longest events within that period. Overall, the results of maximum wet period duration are not as reliable as those of average duration, as they are based on one single event per period.

Looking at the shifts in the frequency distributions of decile wet period duration (Figure 7.47) shows that the declines in average wet period duration are not due to an increased occurrence of very short (≤ 6 months) events, but to more infrequent wet periods of medium duration (7 to 9 months). During the 2nd half of the 20th century, a quite different tendency compared to the entire 20th century was observed. While wet periods, lasting 5 to 6 months, occurred much more frequent in 1951—1975, the frequency of medium durations increased in 1976—2000.

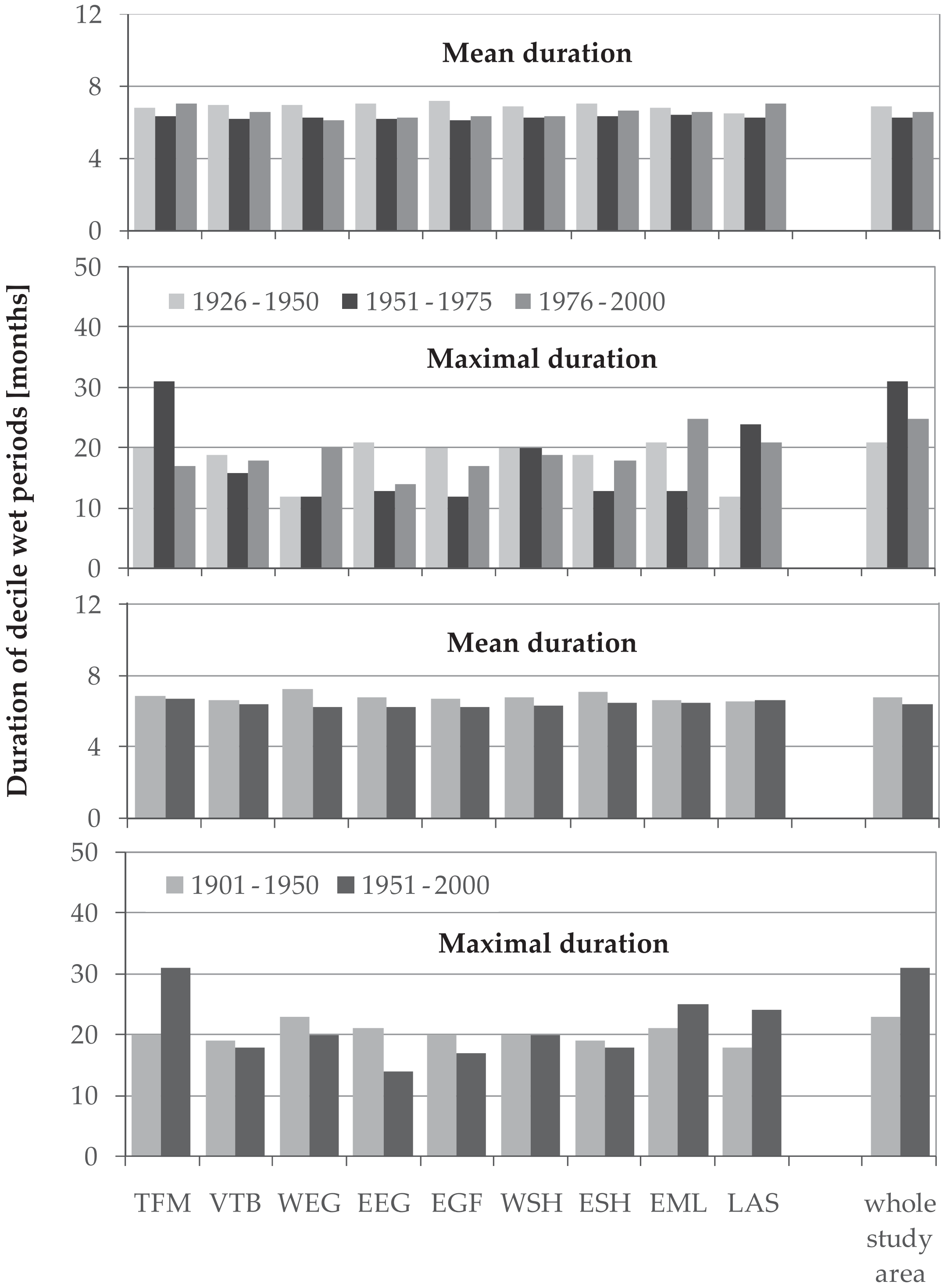


Figure 7.46: Changes in the mean and maximum duration of decile wet periods in the nine regions (130 stations) for 25- and 50-year intervals; 1901—2000

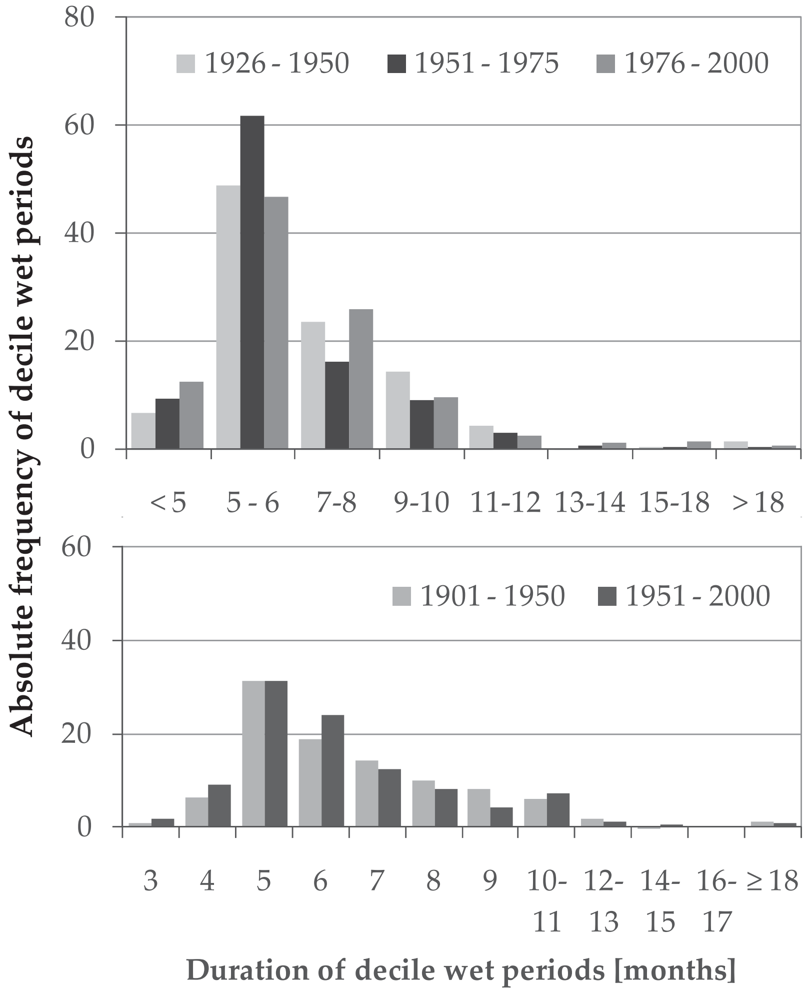


Figure 7.47: Shifts in the histograms of decile wet period duration in the nine regions (130 stations) for 25- and 50-year intervals; 1901—2000

7.3.6 Frequency and Severity of Monthly Wet Extremes and Periods

The RAI and PNI indices are used to get a first impression about changes in the frequency of wet events. Analogue to the approach described in subsection 7.2.2 for the frequency of dry events, the 15 wettest months and years were identified and classified into three time categories (A: 1900—1949, B: 1950—1999 and C: 2000—2006). Both indicators show that the timing of wet years is more equally distributed over the three time categories (Table 7.18, Table 7.19) than the one of dry years (Table 7.7, Table 7.8).

Although both indicators described the changes in dry month frequency quite similarly, there are some differences between the findings of these indicators regarding wet extremes. Using the PNI, the wettest months more frequently belong to the first category for the months January to March, August and November as compared to category B (1950—1999; Table 7.18, Table 7.19). Nevertheless, with the exception of August the highest percentage occurred in category C (2000—2007), indicating an increase in wet extremes during the last seven years. The high percentage of wet PNI extremes in period 1900—1949 may be due to the poor data availability before 1951. With fewer station-PNI available for regional averaging, single extreme station values might by coincidence influence the regional average quite strongly.

The RAI does not confirm the high percentage of wet extremes in category A (1900—1949), suggested by the PNI (Table 7.18, Table 7.19). In the months

Table 7.18: Wettest months and years (Ann) measured by the Percent of Normal indicator PNI and the Rainfall Anomaly Index (RAI) for the whole study area (130 stations) for 1900—2006

		Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Percent of Normal Indicator (PNI)	1	1926	1976	1946	1915	1927	1941	1926	1954	2002	1952	1960	2002	1974
	2	1941	1921	1970	2000	1980	1961	1916	1907	1945	1906	1974	1919	1986
	3	1981	1938	1948	1994	1920	1978	1946	1955	1978	1924	1930	2004	1947
	4	2002	1916	1988	2001	1935	1932	1956	1926	1994	2001	1923	1928	1988
	5	1905	1944	1950	1988	1965	1986	1912	1957	1983	1931	1941	1947	1913
	6	1974	1987	2002	1914	1983	1908	1927	1930	1912	1967	1935	1910	1993
	7	1995	1900	1909	1992	1930	1965	1933	1910	1924	1915	1998	1909	1966
	8	1930	1917	1999	1906	1954	1949	1971	1940	1948	1998	1981	1977	1918
	9	1915	1983	1935	1940	1956	1921	1953	1981	1925	1957	1905	1944	1919
	10	1954	1907	1900	1957	1969	2004	1995	1905	1970	1978	1919	1930	1967
	11	1965	2004	1937	1981	1995	1930	1969	1980	1977	1979	1929	1989	1981
	12	1939	2005	2005	1979	1970	1914	1900	1997	1920	1922	1958	1981	1965
	13	1970	1968	1958	1944	1950	1974	1990	1993	1905	1995	1966	1934	2001
	14	1927	1915	2000	1901	1925	1972	1966	1927	1938	1940	1970	1939	1978
	15	1966	1960	1904	1939	1973	1995	1977	1958	1913	1968	1942	1940	1941
Rainfall Anomaly Index (RAI)	1	1926	1976	1946	2000	1980	1961	1926	1954	2002	1952	1960	2002	1974
	2	1941	1938	1970	1915	1927	1941	1956	1955	1945	1906	1974	2004	1986
	3	1981	1921	1988	1994	1920	1978	1946	1907	1978	2001	1930	1919	1988
	4	2002	1987	2002	2001	1965	1986	1916	1957	1994	1924	1923	1928	1947
	5	1974	1944	1948	1988	1935	1932	1971	1926	1983	1967	1941	1947	1993
	6	1995	1916	1999	1992	1983	1965	1953	1940	1912	1998	1998	1977	1966
	7	1965	1983	1950	1906	1954	1949	1995	1930	1924	1957	1981	1910	1913
	8	1954	1968	1909	1914	1930	2004	1912	1980	1970	1978	1935	1944	1918
	9	1905	2004	1935	1940	1956	1908	1933	1981	1977	1931	1966	1909	1967
	10	1970	2005	1937	1979	1970	1974	1927	1997	1948	1979	1905	1989	1919
	11	1966	1900	2005	1981	1969	1921	1969	1993	1925	1915	1958	1981	1981
	12	1939	1986	1958	1957	1995	1930	1966	1910	2006	1995	1970	1930	1965
	13	1930	1917	1900	1944	1950	1972	1977	1958	1954	1968	1919	1939	2001
	14	1915	1960	2000	2006	1973	1914	1990	1996	1938	1940	1929	1934	1978
	15	1927	1907	1961	1901	1994	1995	1951	1905	1934	1922	1942	1995	1941

1900-1949 1950-1999 2000-2006

January, May, August and October, the percentage of wet RAI extremes within the categories A and B is almost equal. In the months April, June, July, September and December, more wet extremes have been monitored in period 1950—1999 than compared to 1900—1949. Only for November, the frequency in category A is significantly higher than in category B, but the highest percentage of wet extremes occurred in the most recent years 2000—2006. A high frequency in the recent category C furthermore has been observed in the months January to March and August, which is similar to the PNI results.

Generally no changes in the frequency of extremely wet years according to the PNI and RAI indicators have been observed. This is also true for the months May and October, whereas in the other months, more or less pronounced tendencies towards more frequent wet events in the second part of the 20th century or the first years of the 21st century, respectively, occurred. The percentages of the only seven years long period 2000—2006 are, compared to the two 50-year periods, considerably more influenced by coincidence. The case "no event" observed within this much shorter category is not a robust indicator for a decrease in wet extreme frequency in recent times.

The exceedance frequencies of individual thresholds of the PNI and RAI indicators as well as their maximum magnitudes at one station per month or year, respectively, were studied, to receive more reliable information about the changes in the frequency of very wet months, seasons and years. Thereby, the trend results depend more strongly on the chosen threshold and indicator than those of dry events, in particular for the long term trends of 1901—2006 (Table 7.20). Obviously more severe events show other trends than the moderate ones. Explanations for the opposite trends of the indicators in 1901—2006 could be 1) the integration of the 10 most extremely wet cases into the RAI-calculation that delivers some kind of normalisation and 2) the poor data availability before 1951. As the trend pattern for 1951—2006 are quite similar again for both indicators, the last explanation is most probable.

The opposite trend directions of the RAI and PNI indices are illustrated in Figure 7.48 for the annual frequency of RAI-station values above 2 and PNI-station values above 125%. The annual frequency of such events declined according to the PNI, while the RAI indicates a slight increase in the frequency of such events. Before 1951, almost the same percentage of stations exceeded the RAI-threshold of 2 and the PNI-threshold of 125%. After 1951, considerably fewer stations were above the PNI-threshold than compared to the RAI-threshold. This change in the threshold comparability of the RAI and PNI indicator is causing the described opposite trends. Most probably no major changes in the frequency of moderate wet years occurred within 1901—2006.

The trends of the maximum station values of the indicators should be interpreted carefully, as the time series is based on the most extreme value of a single station and thus is quite sensitive to outliers. Due to the rarity of events above the highest thresholds (RAI > 4, PNI > 175%), their trends are also not very robust. Statements about changes in the frequency of severe wet events should therefore be based mainly on the trends of moderate thresholds.

Both indicators show a decline in the frequency of severe wet events in summer and an increase in winter for the periods 1951—2006 and 1901—2006 (Table 7.20). The negative trends are most pronounced and temporally -

Table 7.19: Comparison of the timing of the 15 wettest months and years according to the Percent of Normal Indicator PNI and the Rainfall Anomaly Index RAI (the period with the highest percentage of wet cases is marked for every month)

		Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PNI	**1900–1949**	14.0	16.0	14.0	14.0	10.0	14.0	14.0	14.0	18.0	12.0	16.0	20.0	10.0
	1950–1999	14.0	10.0	10.0	12.0	20.0	14.0	16.0	16.0	10.0	16.0	14.0	6.0	18.0
	2000–2006	14.3	28.6	42.9	28.6	0.0	14.3	0.0	0.0	14.3	14.3	0.0	28.6	14.3
RAI	**1900–1949**	14.0	14.0	12.0	12.0	8.0	14.0	12.0	12.0	14.0	12.0	16.0	18.0	10.0
	1950–1999	14.0	12.0	12.0	12.0	22.0	14.0	18.0	18.0	12.0	16.0	14.0	8.0	18.0
	2000–2006	14.3	28.6	42.9	42.9	0.0	14.3	0.0	0.0	28.6	14.3	0.0	28.6	14.3

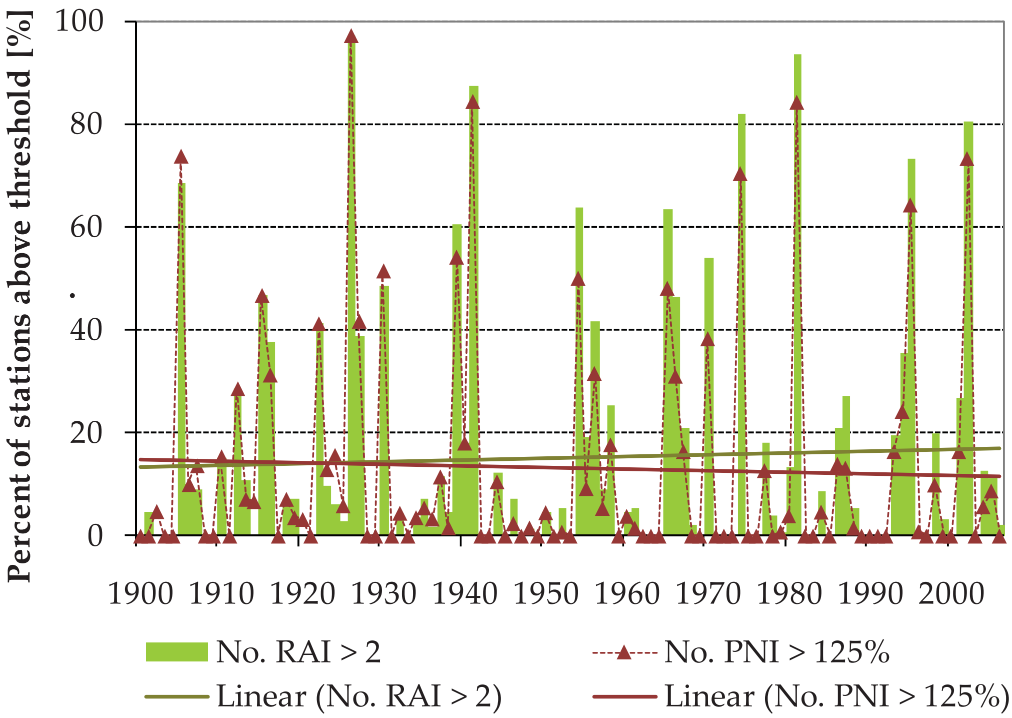


Figure 7.48: Annual time series of the exceedance frequency of the thresholds for moderately severe wet periods (RAI > 2 and PNI > 125%) for 1901—2006

Table 7.20: Monthly and seasonal relative linear trends of the exceedance frequency of individual thresholds of RAI (Rainfall Anomaly Index) and PNI (Percent of Normal Indicator) for period 1901—2006 in comparison to 1951—2006

	1901 — 2006	PNI No. > 125%	PNI No. > 150%	PNI No.> 175%	PNI Max	RAI No. < -2	RAI No. < -3	RAI No. < -4	RAI Max
1901—2006	January	10.6	4.2	-4.8	-4.3	17.3	45.5	122.8	20.2
	February	27.3	40.1	53.7	15.9	108.8	127.6	69.7	68.5
	March	18.7	28.9	52.9	23.4	92.6	172.2	216.1	99.8
	April	-27.2	-35.9	-68.5	-4.3	6.9	-17.6	-16.5	20.6
	May	-7.7	-1.9	-34.9	11.0	33.8	43.2	53.1	59.4
	June	-28.8	-73.5	-118.6	-4.3	-27.6	-44.2	-73.6	36.0
	July	-33.7	-55.6	-79.1	-6.4	-24.0	-31.2	9.8	23.0
	August	-34.6	-19.8	-1.8	14.3	37.0	108.0	197.1	61.4
	September	-7.9	-16.7	-25.0	5.6	8.1	12.4	-28.3	38.0
	October	-55.6	-57.7	-68.0	-12.1	-32.3	18.7	53.8	13.8
	November	-19.4	-42.8	-9.1	11.9	1.8	110.3	194.2	59.8
	December	61.6	76.6	134.6	29.3	102.6	173.6	219.9	108.2
	Spring	-20.1	-24.6	93.4	2.9	13.6	69.5	96.3	38.0
	Summer	-81.6	-140.6	-164.1	-9.2	-70.9	-57.2	-54.8	26.9
	Autumn	-32.8	-21.3	-43.8	-3.6	7.1	28.7	24.1	31.0
	Winter	59.7	46.7	90.5	11.0	94.0	109.2	129.6	63.5
	SHY	-100.2	-145.1	-193.7	-9.6	-66.4	-35.9	37.9	14.2
	WHY	20.9	-39.5	-198.6	6.2	61.2	75.9	145.0	61.5
	Annual	-29.7	-182.9	-285.0	-4.7	18.7	27.7	16.0	15.2
1951—2006	January	74.7	93.3	112.5	-3.5	103.1	75.4	13.1	-12.6
	February	56.3	79.5	102.8	11.8	91.8	115.5	109.7	9.1
	March	47.2	112.4	169.5	17.1	162.2	226.6	319.2	51.2
	April	-93.0	-127.3	-127.5	-22.3	-120.2	-128.0	-91.3	-61.2
	May	14.3	-2.4	-23.8	5.7	-3.7	-25.6	-59.6	13.0
	June	-91.6	-148.5	-193.3	-20.1	-144.2	-175.4	-206.4	-43.1
	July	27.5	-7.5	-57.0	-9.8	-116.7	-269.1	-394.9	-22.7
	August	55.2	95.3	104.9	0.2	93.8	112.7	153.5	-6.5
	September	10.9	-18.1	-28.5	0.8	-23.2	-84.3	-240.9	-4.0
	October	-52.2	-66.0	-84.9	-15.2	-100.6	-138.4	-175.1	-36.7
	November	75.1	135.7	233.1	24.3	161.3	272.1	362.6	47.7
	December	31.2	42.8	50.4	18.5	41.7	51.5	33.9	52.1
	Spring	18.3	-63.7	-2.0	0.2	4.5	-56.1	-66.9	-3.7
	Summer	-59.8	-155.1	-272.6	-10.5	-121.3	-212.3	-288.4	-34.8
	Autumn	42.8	23.2	-51.9	3.0	25.2	-22.7	-159.8	9.1
	Winter	110.7	128.4	175.0	12.9	108.4	110.0	136.7	24.7
	SHY	-68.0	-143.6	-443.7	-8.3	-85.7	-116.0	-162.6	-32.7
	WHY	102.7	37.7	-216.9	15.1	94.0	79.8	5.1	55.5
	Annual	5.8	-4.0	######	-1.9	-3.2	18.3	45.8	-9.7

(blue) less frequent dry extremes ##### no trend computation possible

(orange) more frequent dry extremes

representative in April, June, July and October. Those are the months for which no single of the 15 most extreme events was observed in 2000—2006. In contrast, the increases in the frequency of wet events are highest in the months with a high percentage of extremes in 2000—2006, namely January to March, August, November and December.

Spatially, some differences in the trends of severe wet event frequency evolve (Annex 30), but altogether most regions show quite similar trend directions. Temporally, the trends of wet extremes (Annex 30) are more representative than those of dry extremes (Annex 22). The trend pattern of different periods are most similar for both half years, the summer season and the months March, June, July, October and December. Although the positive February trend pattern are regionally quite similar for the periods starting in 1901 and 1951, trends to less frequent wet extremes predominate for the periods as of 1931 and 1941. A similar tendency was observed for May, but already a higher percentage of regions showed negative trends for the periods starting in 1901 and 1951. The negative April trends have intensified, while opposite developments

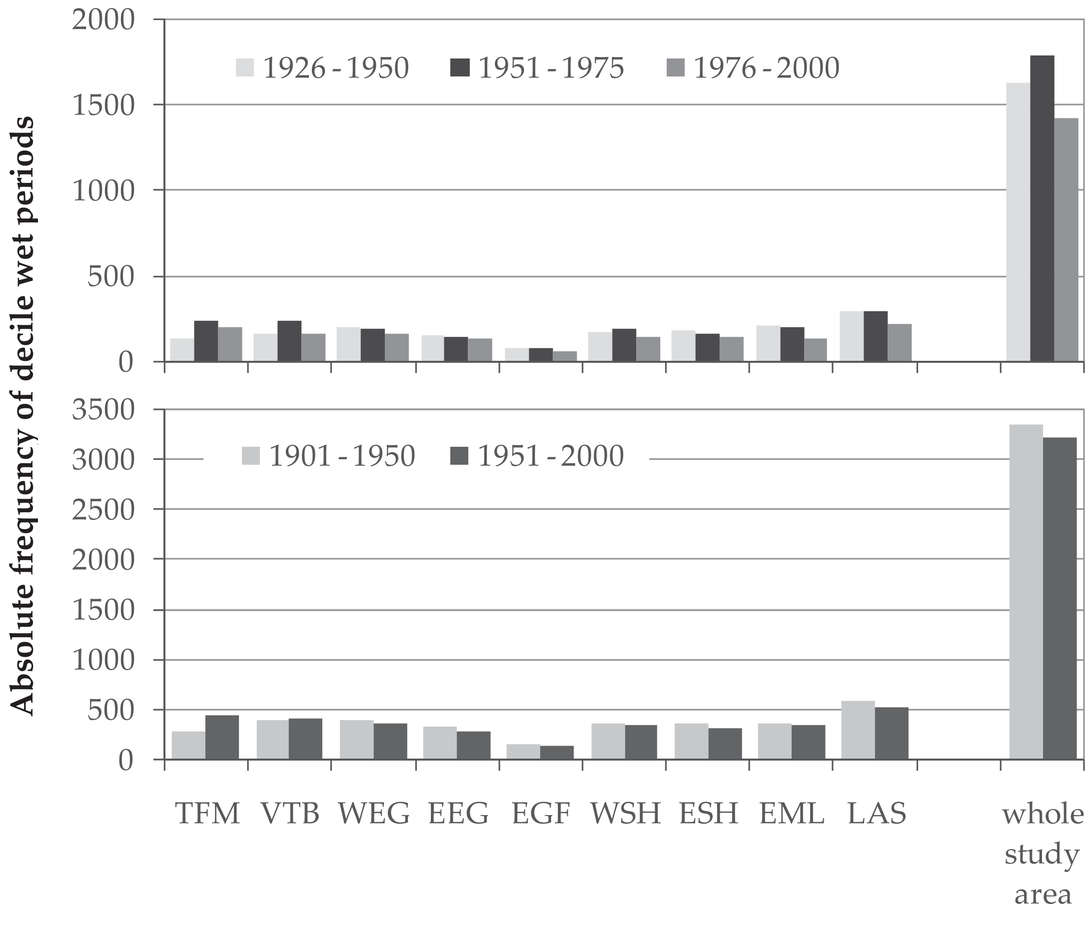


Figure 7.49: Changes in the absolute frequency of decile wet periods within the nine regions (130 stations) for 1901—2000 (results are extrapolated for 100% data availability)

to regionally more frequent positive trends in recent periods were observed for January, August and November.

Long wet periods, as measured by the decile indicator, show slight decreases in their frequency during the 20th century within most regions, particularly pronounced within the second half of the 20th century (Figure 7.49). Only for region TFM, considerably more decile wet periods were observed in 1901—1950 as compared to 1951—2000. Slight increases were also observed in the neighbouring region VTB. Decile wet periods did not only become shorter (sub-section 7.3.4) but also less frequent during the 20th century, whereas the less frequent decile dry periods (sub-section 7.2.2) got longer (sub-section 7.2.1).

7.3.7 Timing of Wet Periods

An approach analogue to the decile droughts (sub-section 7.2.4) was used to analyse changes in the timing of decile wet periods. Although some shifts in the characteristic months in which decile wet periods frequently start or end

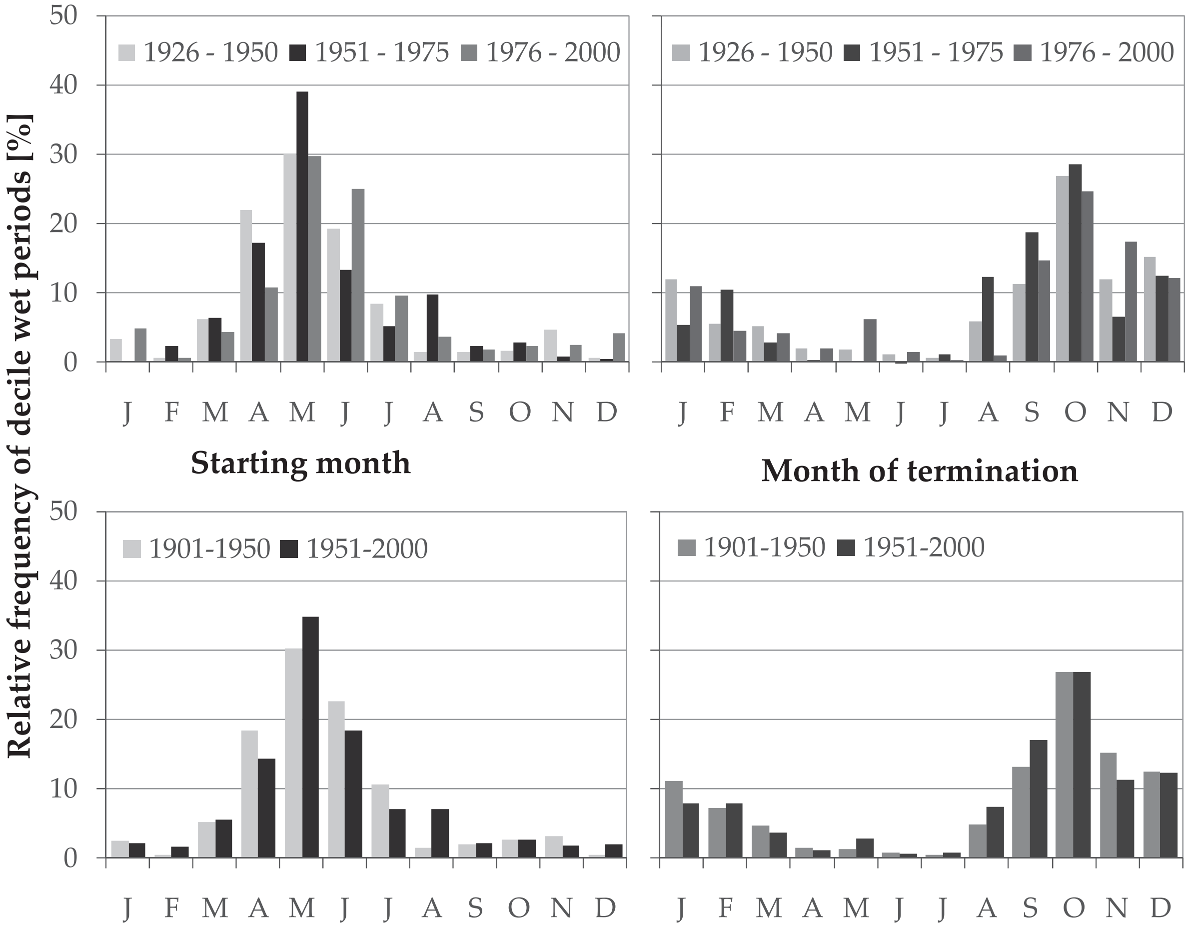


Figure 7.50: Shifts in the characteristic months of decile wet periods start and termination in nine regions in South Eastern Germany (130 stations) for 1901 to 2000

occurred, the general characteristics described in sub-section 6.2.3 stayed the same. The start of decile wet periods has shifted slightly from spring (April, May) to late spring and summer (May to August) during the 20th century (Figure 7.50). This shift is probably due to the general precipitation decreases during the vegetation period. Regarding the months of decile wet period termination, no uniform changes have been observed. The observed slight shifts might just be caused by coincidence.

7.3.8 Spatial Characteristics of Wet Periods

Similar to decile dry periods (sub-section 7.2.5), long term changes in the spatial characteristics of decile wet periods occurred within the 20th century. But in contrast to dry periods the spatial coverage of wet events has decreased from 1901 to 2006, as it did for the shorter periods of 1931—2006 and 1951—2006 (Figure 7.51). Similar to the approach used for decile dry periods, the reliability of the trends was checked using only stations with long term data. The results are quite independent from the number of stations (Figure 7.51). The negative slopes of the trend lines are of similar magnitude for all three periods and for both base data (22 and 130 stations). The spatial extension of decile wet periods declined during the last century, indicating changes in large scale atmospheric circulation pattern. Small scale convective precipitation events seem to gain influence on the formation of decile wet periods compared to large scale triggers. This is in accordance with the results of decile droughts for the recent periods of 1931—2006 and 1951—2006.

The regional trend developments of decile wet period coverage are a little bit more heterogeneous than for decile dry periods. Negative trends for all three periods have been observed in the regions VTB (Vogtland and Thuringian Basin), EGF (Erzgebirge Foreland), WSH (Western Saxon Hilly Country), ESH (Eastern Saxon Hilly Country) and LAS (Lausitz and Spreewald). In the regions VTB and LAS, the decrease in spatial wet period coverage is most pronounced in the most recent period 1951—2006. In contrast, almost no changes in the percentage of wet period affected stations were observed during this period in the Erzgebirge regions (WEG and EEG) and in the 'Thuringian-Franconian Mountains' (TFM). The long term trends of 1901—2006 are negative within all regions except TFM, where no trend may be computed for that period and EML (Elbe-Mulde Lowlands), showing no changes in wet period coverage during the last century. Region EML has also been the only region with an opposite trend in long term decile dry period coverage compared to all other regions (sub-section 7.2.5). Increases in the percentage of stations affected by decile wet periods have only been observed in region TFM for period 1931—2006.

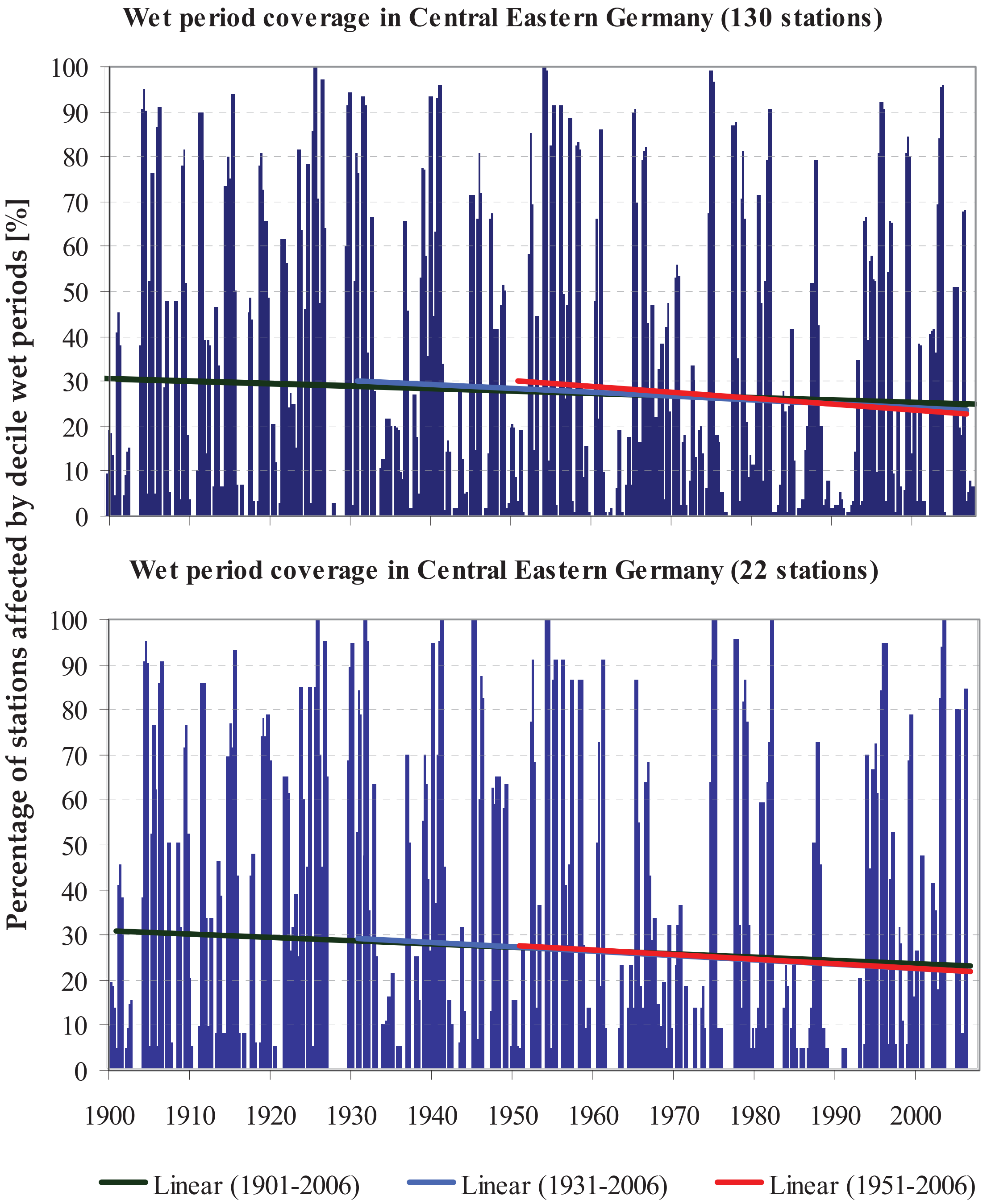


Figure 7.51: Regional coverage of decile wet periods over the whole study area (130 stations) and for selected stations with long term data (22 stations) for 1900—2006

7.3.9 Resume

Changes in intensity, frequency and spatiotemporal characteristics of daily and monthly wet extremes were studied using several Heavy Precipitation Indicators (HPI) as well as the indicators RAI and PNI. The decile indicator was used to analyse changes in duration, frequency, timing and spatial coverage of wet periods. Opposite trends of wet extremes are possible, depending on the rarity of investigated events. Generally, the trends of moderate extreme heavy precipitation events are more robust and significant than those of the more extreme events, as accidental occurrences or outliners strongly influence the trends of extreme events.

Severely wet years, seasons and months, identified by the indicators PNI and RAI, were more equally distributed over the study period than dry extremes. Thus, they less often showed regionally homogenous and significant changes. Nevertheless, the temporal representativeness of wet extreme trends is higher than for dry extremes for most months and seasons; in particular for both half years, the summer season, March, June, July, October and December. Differences between the trend results of both indicators might be quite high. For example, the PNI indicated a high frequency of wet extremes in the first half of the 20th century for January, February, March, August and November, not confirmed by the RAI. The results before 1951 may be influenced by the poor data availability, delivering less robust secular regional trends than compared to 1951—2006. Furthermore, the integration of the ten most extreme wet events into the RAI calculation might explain some of the observed differences in PNI and RAI trends. Generally the different trend directions of RAI and PNI for 1901—2006 are due to a change in the comparability of the indicator thresholds occurring at about 1950.

Many indicators show indifferent annual trends, matching the average precipitation trends. Only the maximal one-, three- and five-day precipitation totals decreased in all regions. This is due to decreasing precipitation trends during the SHY, as the highest precipitation events per year mainly occurred during the summer season. Significant annual HPI, RAI and PNI increases were mainly found in region TFM, showing the highest increases in precipitation averages, while decreases were most significant in the north-eastern regions EML and LAS with the most pronounced precipitation decreases.

HPI, PNI and RAI trends are predominantly negative during the SHY, while positive trends dominate in the WHY. Nevertheless, the percentage of negative/ positive HPI trends for the SHY/ WHY was lower than compared to average precipitation indices, true for both half years. Significant developments mainly occurred in the regions EML and LAS for the SHY and in region TFM for the WHY, as noticed for annual trends.

The seasonal trends are generally less significant than the half year trends. Overall, the seasonal and monthly trends follow the average precipitation trends, with more frequent and severe heavy precipitation events on daily and monthly time scales, in months and seasons with general precipitation increases. The results of average and extreme precipitation indices were most similar for July, August, October, November and December. But there were also months and seasons for which HPI suggested developments opposite to the trends of average precipitation, particularly for the more extreme events. This applies to January, showing decreases in most HPI, despite general precipitation increases. In contrast, the frequency and magnitude of heavy precipitation events increased at a comparatively high percentage of stations from April to June, although those months were characterised by distinct precipitation decreases.

Most regionally homogenous and frequently significant increases in HPI were observed for March, November and December, although significant trends were considerably less frequently observed in the north-eastern regions ESH, EML and LAS. Decreases in HPI were most pronounced in February, July and October, except for the region TFM. During August HPI indicate significant increases in frequency and severity of heavy precipitation events for the Erzgebirge (WEG, EEG).

The high natural variability of precipitation was reflected in the moving 30-year trend analysis, showing temporarily and spatially quite variable trends for annual and seasonal HPI time series. More homogenous developments with similar trend directions and timing of trend reversal in most regions occurred in February, July, October, November and December, quite independent from the chosen threshold and the connected rarity of the events. Generally the trends of the more extreme HPI were temporarily and spatially more variable and thus less representative than those of moderately extreme events.

Frequency, duration and regional coverage of decile wet periods declined slightly during the 20th century. The decreases in average duration were least pronounced in the regions EML and LAS. Slight increases in decile wet period duration occurred within the second half of the 20th century, while the decreases in frequency were more pronounced than for the entire study period. The onset of decile wet periods became more frequent in July and August and less frequent in April in recent times, while no uniform changes for the characteristic drought termination months were found. The decline in spatial wet period coverage agrees with the results for the spatial extent of decile dry periods in recent decades, both indicating changes in the large scale atmospheric circulation pattern and a rising influence of small scale convective precipitation events.

In summary, the trend results of daily and monthly wet extreme indicators were quite similar and basically match the general precipitation changes, particular for moderately wet extremes.

8 Relations between selected Indices

8.1 Comparison of Drought and Dry Period Indicators

Dry periods have been described using different indicators; some based on monthly others on daily precipitation data. Dry events of different duration and timing are the result. Therefore, it is no surprise that some of the indicators might indicate opposite trend directions for the frequency or duration of dry periods. More frequent or longer lasting short dry periods do not necessarily have to be connected with more frequent or longer lasting long term drought conditions. Hence, it is very important to consider the intention and informative value of individual drought indices for the interpretation and comparison of their trends.

Generally, the monthly indicators quite similarly describe dry events and their connected changes in the 20th century. A filter averaging the monthly PNI and RAI indicators over 12 periods was used, to smoothen the highly variable monthly indicator time series (Figure 8.1). The PNI time series is characterised by larger deviations from normal conditions (RAI = 0 and PNI = 100%). This is particularly true for positive anomalies that are not limited above. The correlation coefficients of PNI and RAI time series for individual stations range from 0.94 at stations in region LAS to 0.98 in regions TFM and VTB.

The high correlations of the RAI and PNI time series demonstrate that the drought frequency trends, as defined by those indicators, are quite similar. For the annual time series, the frequency of falling below a PNI value of 75% is considerably smaller than the frequency of drought events defined by a RAI value below -2 (Figure 8.2a). Nevertheless, the connected trends are quite similar; the RAI indicates a slightly more pronounced increase in the frequency of drought years between 1901—2006 than the 'Percent of Normal Indicator'.

For the half years, the frequency of falling below the thresholds for a drought event is almost the same for both indicators. The positive summer half year trend, however, is again higher for the RAI than for the PNI (Figure 8.2b). Those differences in the trends are due to a change in the comparability of the thresholds for defining dry conditions of both indicators emerging at about 1950. Before that time, almost the same percentage of stations fell below a RAI value of -2 and a PNI value of 75%, but after 1950 a considerably higher percentage of stations indicate drought conditions according to RAI rather than based on PNI. This observation might be due to the poor data availability before 1951, as fewer stations are available for calculating the percentage of stations below a certain threshold. But this assumption is quite implausible, as such a change in threshold comparability was not observed for the winter half year (Figure 8.2c). Another explanation could be the integration of the 10 driest summer half years into the RAI calculation; six of them have been observed in the second part and only four in the first part of the 20th century. This could lead to an overestimation of drought conditions at the beginning of the 20th century by the PNI that does not include the absolute size of the most extremely dry events into its calculation.

The comparison of RAI and PNI to the other drought indicators is limited, as RAI and PNI do not deliver dry periods in terms of drought duration with a fixed onset and end. On the first hand, they just give information about the frequency and severity of drought conditions in single months and seasons and thus allow a climatologic assessment of the connected water availability for individual sectors. The other drought indicators used within this study assess the duration of dry events at different time scales. For this purpose, different thresholds for the onset and termination of drought conditions are used for daily and monthly precipitation time series, yielding dry periods of quite different duration. Information about drought severity and its changes cannot directly be observed from those indices.

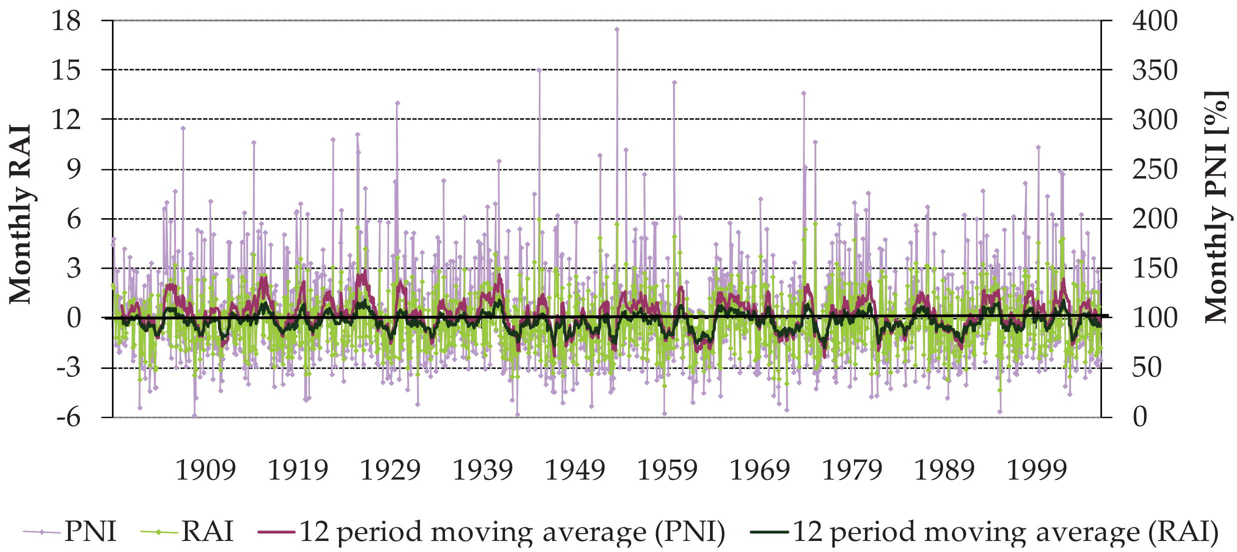


Figure 8.1: Monthly PNI and RAI time series (averaged for all 130 stations) with 12 period moving average for 1900—2006

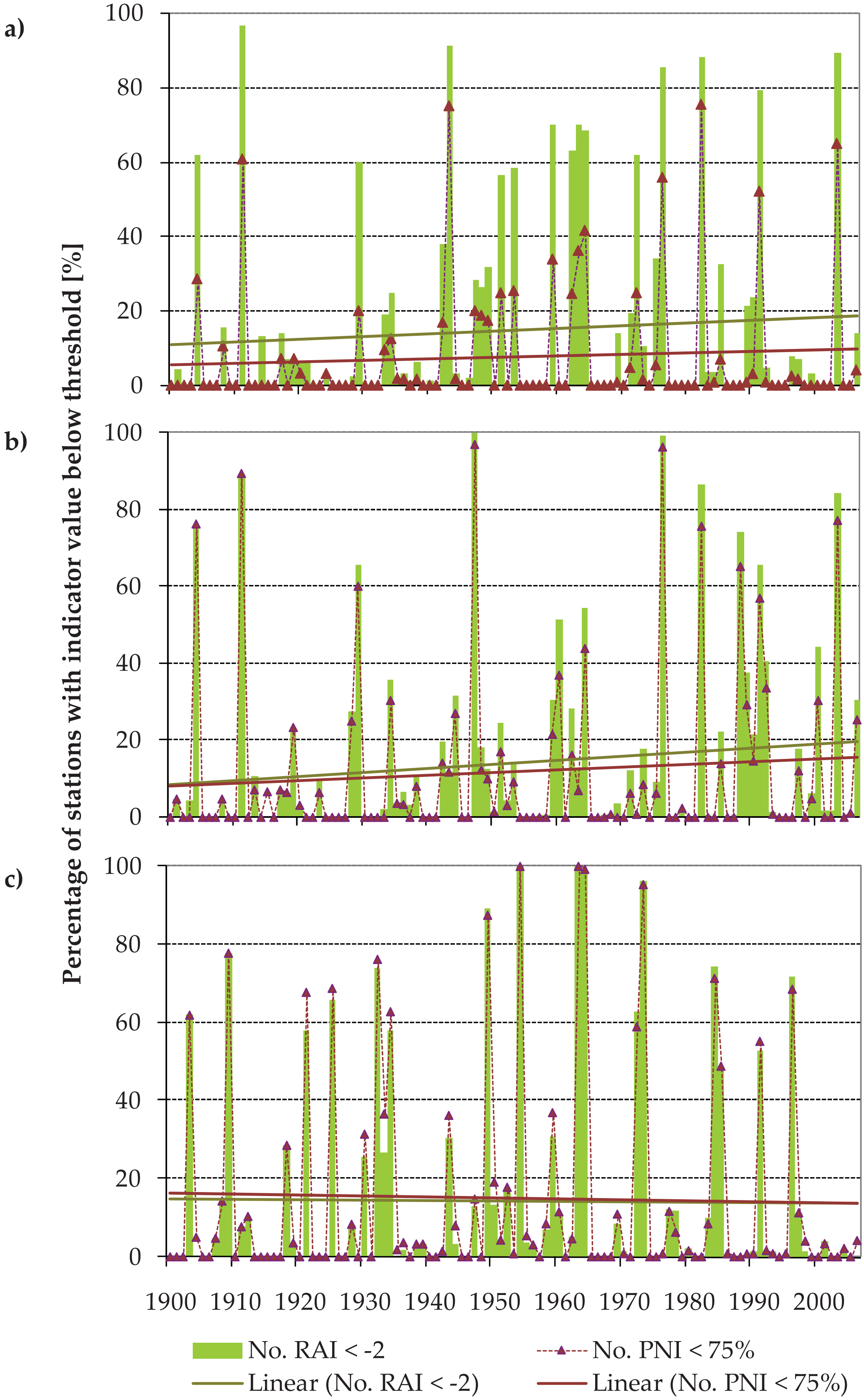


Figure 8.2: Time series of the frequency of drought events defined as RAI-values below -2 and PNI-values below 75% with linear trends for a) the whole year, b) the summer and c) the winter half year for 1900—2006

Timing and duration of dry periods delivered by several drought indicators, based on monthly and daily precipitation data, are compared for station 'Fichtelberg' situated in region WEG (Figure 8.3). This station was selected, as it has the longest daily precipitation record within the study area, starting in 1918. Monthly precipitation data are even available as of 1900. Generally, the comparability of dry period timing and duration derived from monthly and daily time series is very limited, as different time scales are concerned. Although short meteorological dry periods may occur frequently in times of long-term drought conditions indicated by the decile index, they may also occur quite frequent in other times (Figure 8.3). DPST-75% dry periods occur very frequently. Due to the compressed time-scale in Figure 8.3, dry periods appear to occur almost the whole time, but of course they do not.

The drought occurrence delivered by a daily indicator is most similar to the decile dry periods, based on three-month precipitation totals, if only DPST-75% dry periods lasting at least three months are displayed (Figure 8.3e). But still there are major differences, due to the different calculation approaches. Although DPST drought might last several months or even years their onset and termination is mainly influenced by daily and weekly precipitation extremes. In contrast, decile droughts depend on deviations in three-month precipitation totals that might level single daily extremes. The relevance of those indicators has to be evaluated individually for every application area.

Comparing the monthly indicators of drought severity PNI and RAI to the decile dry period indicator shows that decile droughts generally occur at times with negative PNI or RAI anomalies over a longer period (as indicated by the 12 period moving average of those indicators). Again station 'Fichtelberg' is used as an example. In Figure 8.4 only the monthly RAI time series is displayed in comparison to the decile drought occurrence, as RAI and PNI have a very high correlation.

The results for the indicators, based on daily precipitation data, strongly depend on the thresholds for defining the onset and termination of drought. The comparatively short and severe meteorological dry periods (duration of a few weeks with almost no rainfall) often show opposite trend developments than the longer DPST-dry periods (duration of a few months up to years). The direction and significance of 1951—2000 trends for individual dry period indicators are displayed in Figure 8.5 for the summer half year, in Figure 8.6 for the winter half year and in Annex 32 for the seasons and months.

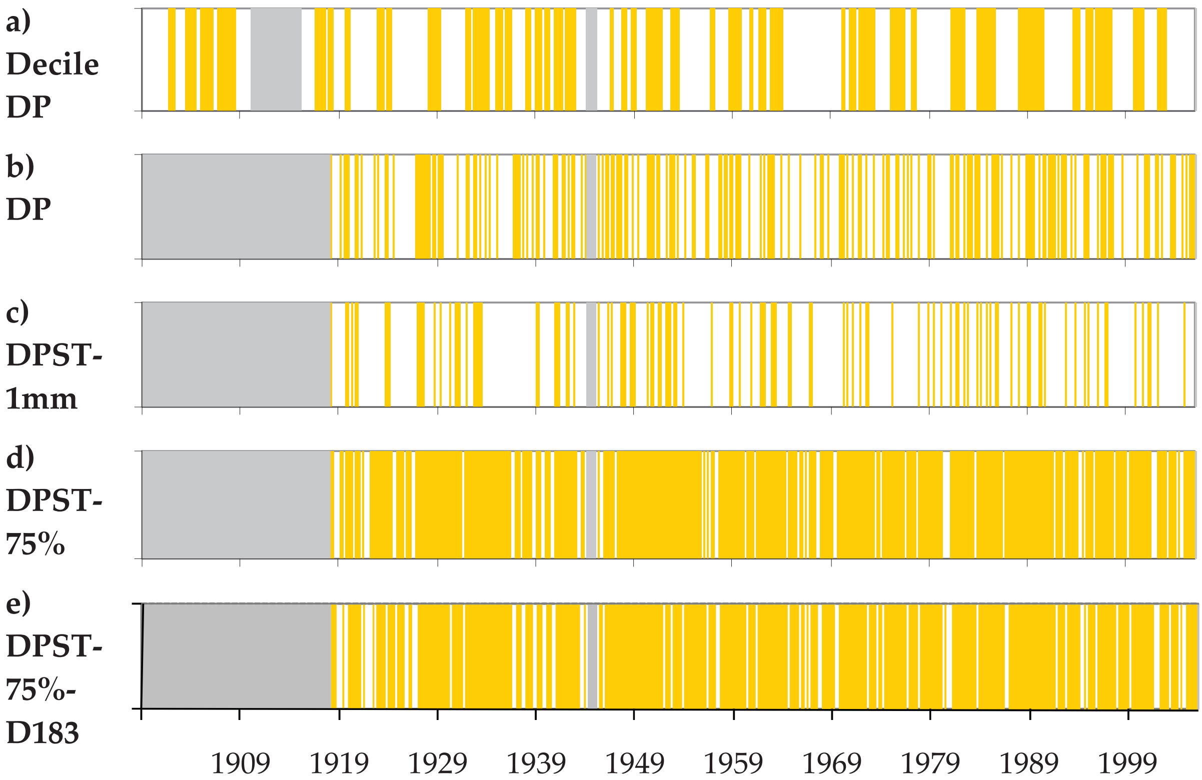


Figure 8.3: Comparison of the timing of dry periods (orange bars) using various drought indicators: a) decile dry periods, b) meteorological dry periods, c) DPST-1mm droughts, d) DPST-75% dry events and e) DPST-75% dry periods lasting at least three months at station 'Fichtelberg' (WEG) for 1900—2006 (grey bars indicate missing data)

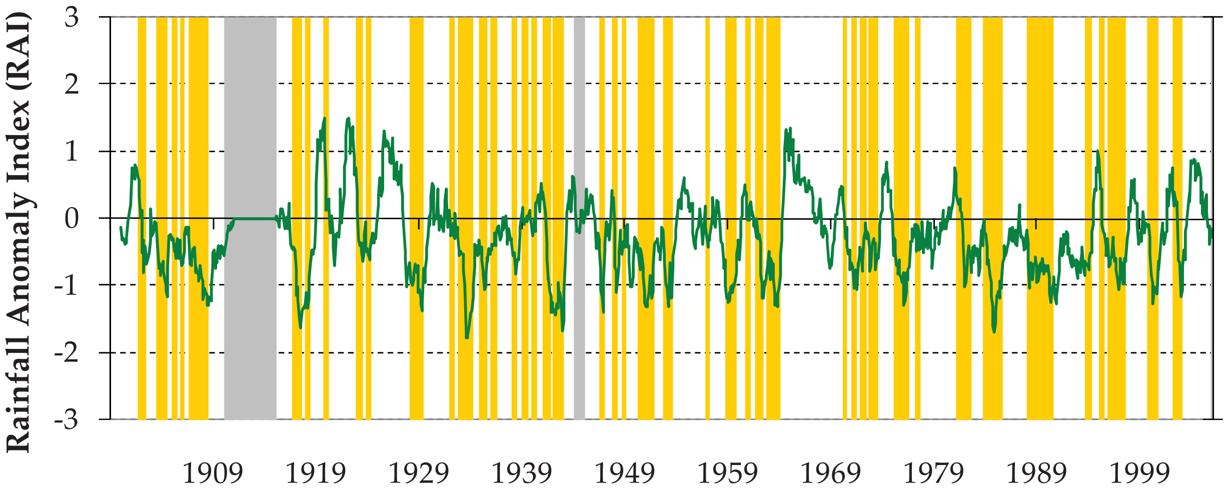


Figure 8.4: Comparison of the timing of decile dry periods (orange bars) with the 12 period moving average of the monthly RAI time-series (green line) at station 'Fichtelberg' (WEG) for 1900—2006 (grey bars indicate missing data)

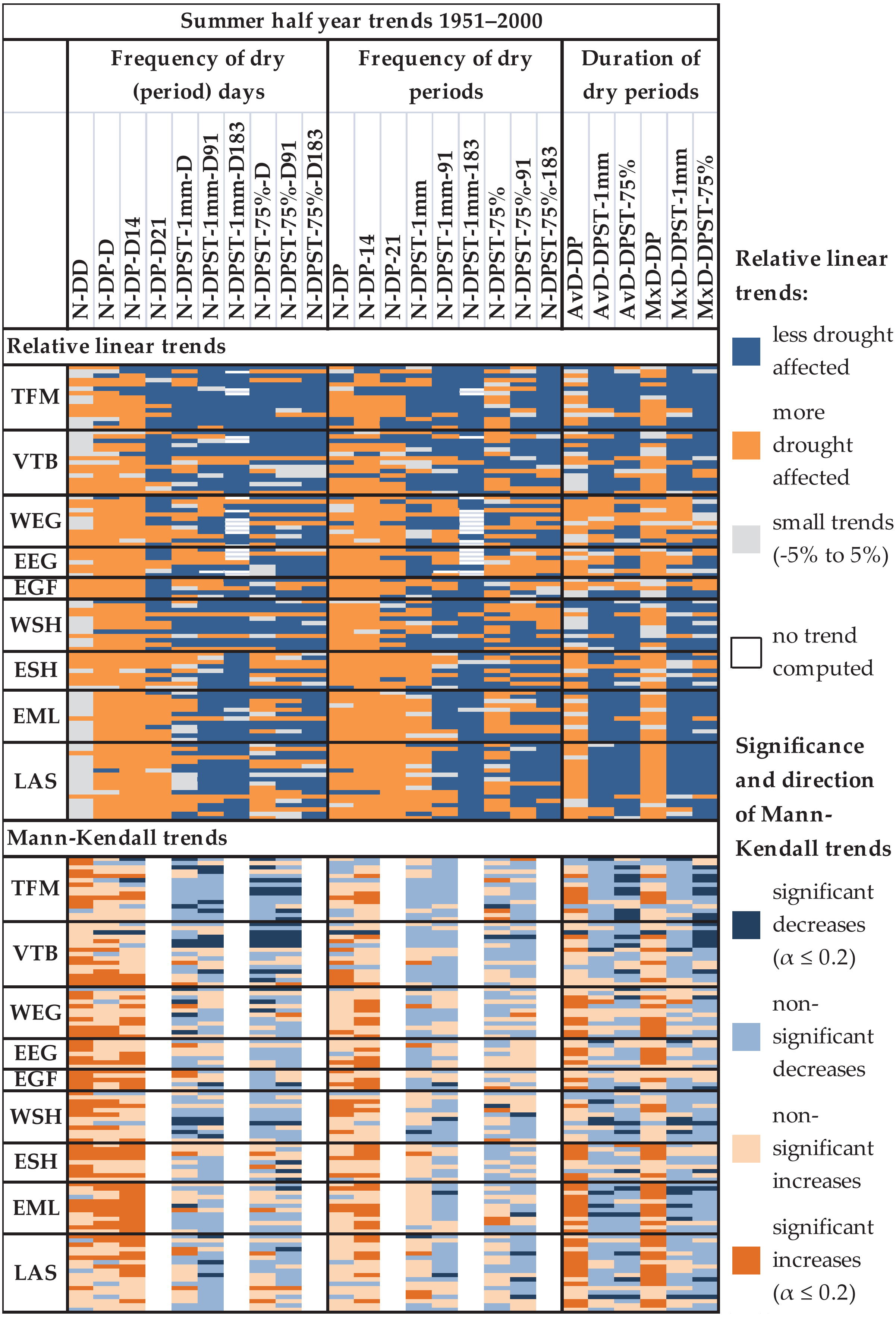


Figure 8.5: Diagram of the summer half year trends of different meteorological dry period indicators expressed as relative linear trends and Mann-Kendall trends for 1951—2000

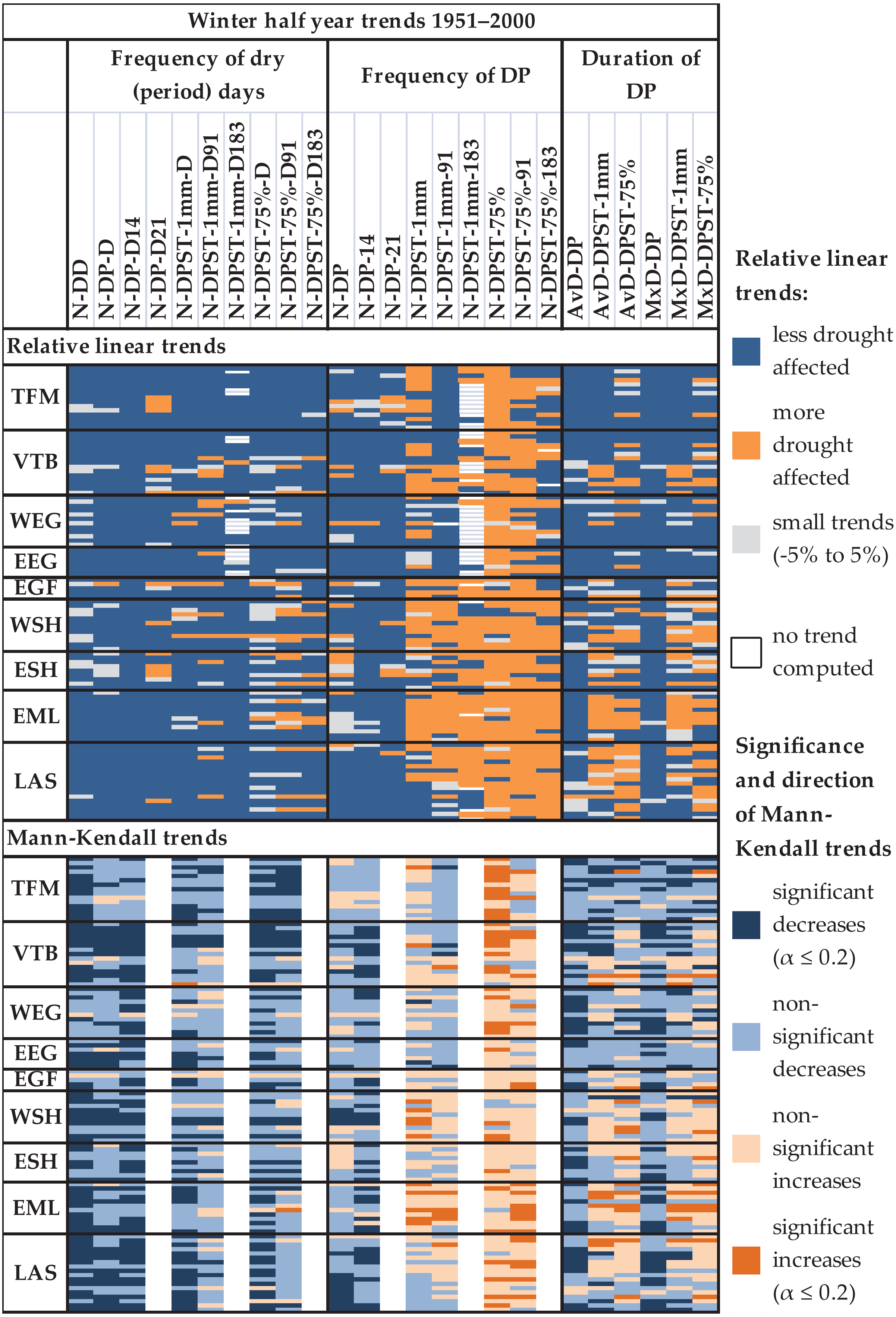


Figure 8.6: Diagram of the winter half year trends of different meteorological dry period indicators expressed as relative linear trends and Mann-Kendall trends for 1951—2000

Based on daily precipitation drought indicators the annual frequency of dry period days as well as the duration of dry periods has decreased slightly, quite independently from the chosen indicator (Annex 32). A high percentage of positive trends were calculated only for the frequency of such periods. The decreases in the frequency of days assigned to dry periods and the dry period duration were most frequently significant (Mann-Kendall trend test) in the south-western regions TFM and VTB. The opposite trend directions of dry period frequency and duration indicate that dry periods are more often interrupted by heavy precipitation events and periods in recent times, leading to shorter but more frequent droughts.

The annual trends of drought duration (sub-sub-section 7.2.1) and frequency (sub-sub-section 7.2.2) according to the decile indicator (based on three-month precipitation totals) are opposite to those of meteorological and DPST dry periods (based on daily precipitation data). This emphasises the importance of considering the underlying time scale of the drought indicator. Decile dry periods got longer lasting but less frequent during the 20th century. Daily precipitation extremes leading to the termination of meteorological and DPST dry periods probably lose influence, when precipitation is summed up to three-month totals. Nevertheless, the recent decreases in spatial decile drought coverage (sub-section 7.2.5) indicate an increasing influence of small-scale convective precipitation events. This is in agreement with the findings of the meteorological and DPST dry period indicators.

During the summer half year (Figure 8.5) and season (Annex 32), short meteorological dry periods became significantly more frequent and longer lasting, whereas the trends for the longer DPST dry periods are more diverse and less significant. Although there are some tendencies towards more frequent DPST events, their duration has declined at most stations. Positive trends for DPST frequency and duration are mainly found in the Erzgebirge regions (WEG and EEG), but the significance of those changes is quite low according to the Mann-Kendall trend test. Significant decreases in DPST duration and the frequency of DPST days are most pronounced in the South-western regions TFM and VTB.

Most drought indicators suggest that the study area became less drought-affected during the winter half of the year. The frequency and duration of meteorological dry periods as well as the frequency of days assigned to meteorological and DPST dry periods have decreased at most stations with a high percentage of significant Mann-Kendall trends. Only for DPST droughts frequency widespread increases have been observed. For the absolute threshold (increasing the threshold by 1mm per continuing dry period day) those increases are most pronounced and significant in the north-western regions WSH and EML. In those regions, also the maximum duration of DPST droughts shows the most frequent and significant increases, independently from the chosen threshold (absolute or relative). For the relative threshold (increasing the threshold for drought termination by 75% of normal daily precipitation per continuing dry period day) positive trends in DPST frequency have been calculated for all regions; most frequently significant are the trends in the South-western regions TFM and VTB. Other than for the summer season and half year, the meteorological and DPST dry period trends of the winter season are quite different from those of the winter half year for some indicators (Figure 8.6 and Annex 32). In the winter season, the duration of dry periods has increased for all indicators in all regions (apart from TFM and WEG) with frequent significant Mann-Kendall trends in the regions EML and LAS. A comparatively high percentage of positive winter trends have been furthermore calculated for the frequency of meteorological dry periods and dry period days, particularly in region TFM. The autumn trends are generally more similar to the winter half year trends than those of the winter season.

Monthly trends in dry period duration and frequency are not as reliable as the seasonal ones, particularly for long-term drought conditions as measured by the DPST concept. But there are some months with quite homogenous spatial trend pattern for the meteorological dry period indicators. For example, May and August show a very high percentage of positive and significant trends for the meteorological dry period (day) frequency and duration (Annex 32).

8.2 Comparison of Heavy Precipitation and Wet Period Indicators

Changes in extreme precipitation were analysed by means of numerous indicators. Monthly and seasonal wet extremes were examined using the indicators RAI and PNI, next to the analysis of heavy precipitation indices based on daily precipitation data. Wet periods of at least three months duration were studied through the decile indicator. Due to the entirely different underlying concepts of heavy precipitation and decile wet period indicators, a direct comparison of their trends is not appropriate. In contrast, comparisons between daily and monthly wet extremes are very well possible.

First, the indicators, monitoring monthly and seasonal wet extremes, namely RAI and PNI, are compared. The annual frequency of exceeding the thresholds for wet conditions are quite similar, unlike for dry extremes (previous section) measured by those indicators (Figure 8.7a). Particularly before 1951, almost the same percentage of stations exceeded a RAI of 2 and a PNI of 125%. After the 1950's, less stations exceeded the PNI threshold as compared to the RAI threshold. This change in the threshold comparability causes the observed opposite trend directions in the frequency of wet years. Possible explanations for the change in threshold comparability have already been discussed in section 8.1.

The differences between the RAI and PNI indicators are considerably higher for the half years than for the annual time series (Figure 8.7). The PNI threshold of 125% is more frequently exceeded than the RAI threshold of 2; probably due to the missing normalisation of the PNI indicator that is limited below. The differences between PNI and RAI are particularly pronounced during the first part of the 20th century. The related half year trends indicate changes in the same direction but with quite different magnitudes, due to the described change in the comparability of the indicator thresholds. The frequency of monthly wet extremes has generally decreased during the summer and increased during the winter half year.

Figure 8.8 compares the filtered monthly RAI time series that is highly correlated with the PNI time series, with the timing of decile wet periods. Analogously to decile droughts, decile wet periods generally occur in times of continued positive PNI or RAI anomalies, respectively. This is again demonstrated for station Fichtelberg in the Western Erzgebirge. As the 12 period moving averages of the RAI and not the very variable RAI time series itself is displayed, decile droughts occur in those periods with large positive slopes of the 12 period moving RAI average.

Comparing the timing of monthly wet extremes, measured by the indicators PNI and RAI with monthly time series of daily heavy precipitation extremes, delivers a quite high correlation between the individual indices (Figure 8.9, Table 8.1). Those correlations are particularly high for moderately extreme heavy precipitation events, as measured by the indicators calculating the frequency or magnitude of the 90th or 99th percentile, respectively. Figure 8.9 displays the 12 period moving averages of percentile magnitudes (Mgt-90P, Mgt-95P and Mgt-99P) in comparison to the RAI for station Fichtelberg. The percentile magnitudes were calculated using approach "ad". A high percentage of the variability of monthly wet extremes may be explained by the occurrence of moderately extreme precipitation events, as demonstrated by their high correlation coefficients for station Fichtelberg in Table 8.1. Despite those comparatively high correlations between daily and monthly wet extremes, the correlations between different monthly indicators are considerably higher.

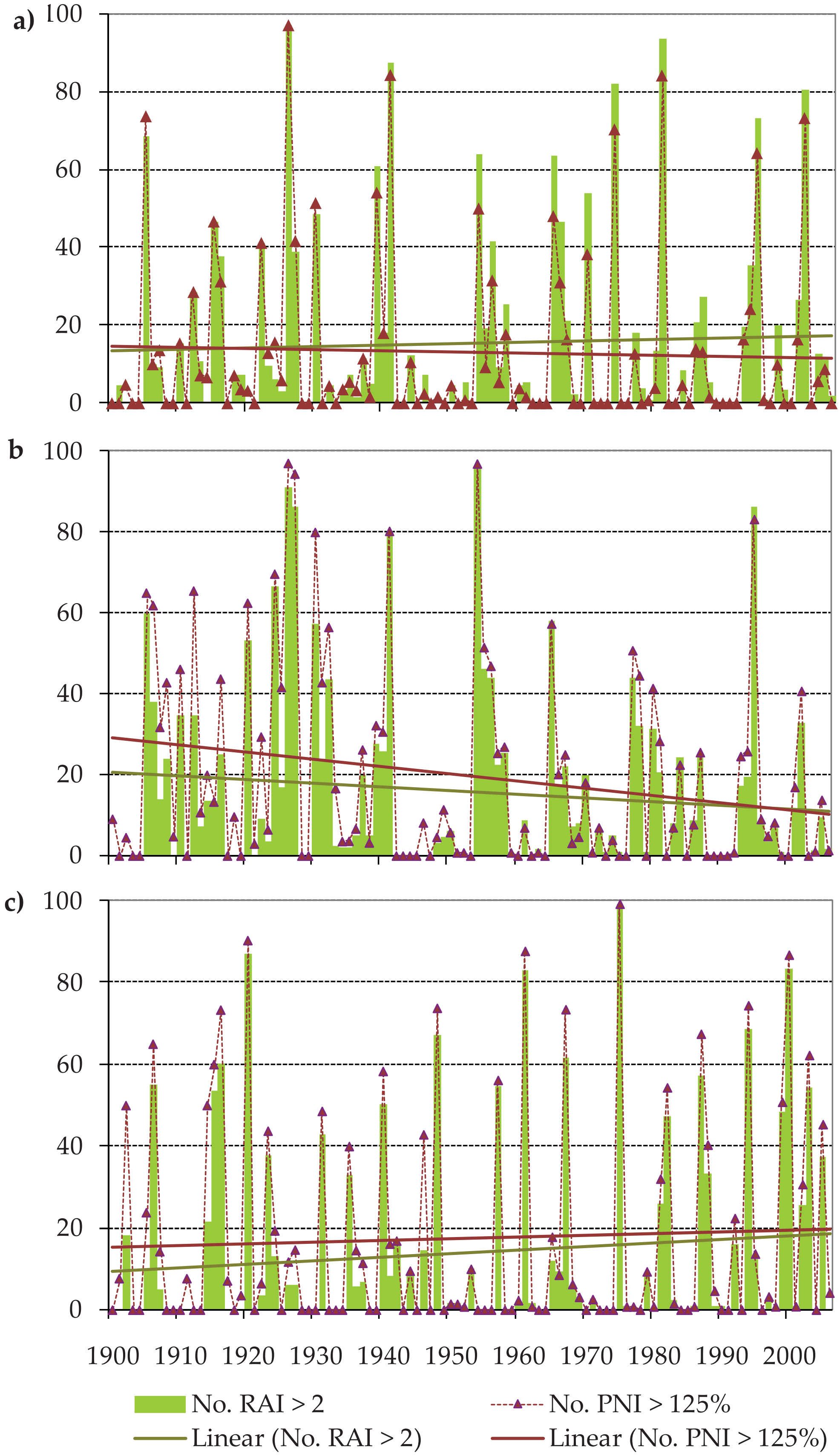


Figure 8.7: Time series of the frequency of wet events defined as RAI-values above 2 and PNI-values above 125% with linear trends for a) the whole year, b) the summer and c) the winter half year for 1900—2006

The trends of 'Heavy Precipitation Indices' (HPI) strongly depend on the chosen threshold and the connected rareness of the studied events (Annex 33), as already described for dry period indicators based on daily precipitation data in section 8.1 (Annex 32). The annual HPI trends are regionally quite heterogeneous for the period 1951—2000, particularly in the regions VTB, WEG, EEG, EGF, ESH and WSH. Although increases in the frequency of wet and

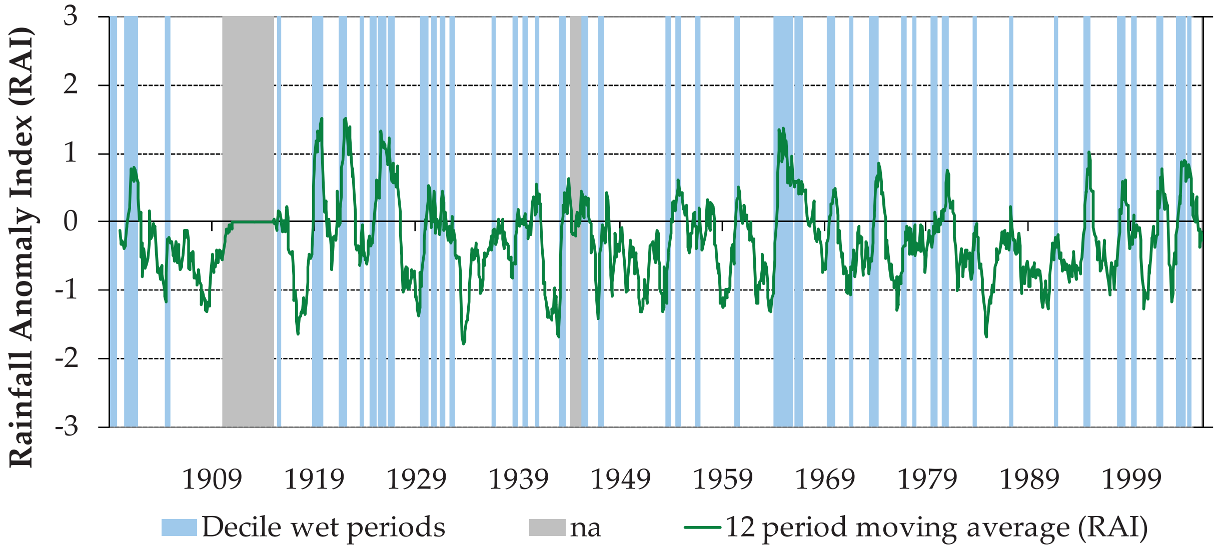


Figure 8.8: Comparison of the timing of decile wet periods (blue bars) with the 12 period moving average of the monthly RAI time-series (green line) at station 'Fichtelberg' (WEG) for 1900—2006 (grey bars indicate missing data)

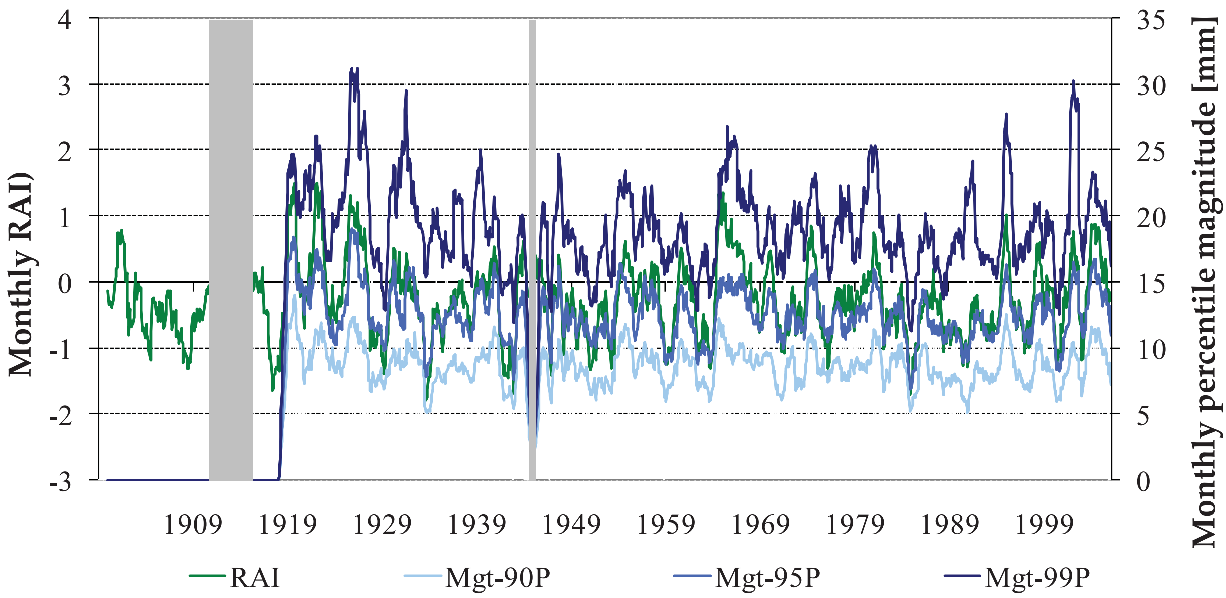


Figure 8.9: Comparison of the 12 period moving averages of a monthly indicator for wet extremes (RAI) and daily heavy precipitation indices (magnitude for the 90th, 95th and 99th percentile calculated for approach "ad"); 1900—2006 (grey bars indicate missing data)

rain days predominate in the regions TFM, EML and LAS, most HPI indicate a decrease in frequency and magnitude of heavy precipitation events in regions EML and LAS, while region TFM is characterised by frequent increases. Predominantly negative trends in all regions were observed for the maximum daily as well as three and five-day precipitation totals only. Those decreases are most frequently significant in the regions VTB, EML and LAS. Significant negative HPI-trends generally most often occur in the regions EML and LAS, while region TFM is characterised by the most frequently significant positive Mann-Kendall trends. Exceptions are the maximum daily precipitation total for TFM and the frequency of wet, rain and dry days for EML and LAS.

Decreasing HPI-trends predominate the summer half year (SHY, Figure 8.10) and the summer season during 1951—2000 (Annex 33), although the percentage of positive trends increased for the frequency and magnitude of higher thresholds (20 mm, 95th and 99th percentile) as well as for the percentage of precipitation above the 95th percentile. Thus, more frequent or severe heavy precipitation events are possible during the SHY, despite general precipitation decreases. Regionally the decreasing HPI trends in the north-eastern regions EML and LAS are most homogenous and most frequently significant for all indicators.

In contrast, the winter half year (WHY, Figure 8.11) as well as the winter season (Annex 33) are dominated by positive HPI trends for most indicators for 1951—2000. Opposite to the SHY trends, the WHY trends became most frequently negative for higher thresholds and thus more extreme heavy precipitation events. Only for the south-western region TFM all HPI indicate increases in wet extremes, with a high percentage of significant Mann-Kendall trends. Increasing precipitation totals do not necessarily have to be connected with more frequent and severe daily precipitation extremes.

The spring and autumn trends of 1951—2000 are spatially more heterogeneous than those of the two other seasons (Annex 33). Increases in most HPI indicators were observed in region EML and parts of LAS for spring and in regions

Table 8.1: Pearson product moment correlation coefficients for several indicators of daily precipitation events and monthly wet extremes

	RAI	N-10mm	N-20mm	N-90P-ad	N-95P-ad	N-99P-ad	Mgt-90P-ad	Mgt-95P-ad	Mgt-99P-ad	Mx-R
RAI	-	0.82	0.65	0.85	0.81	0.57	0.83	0.82	0.70	0.65
PNI	0.97	0.83	0.67	0.87	0.84	0.61	0.84	0.82	0.70	0.65

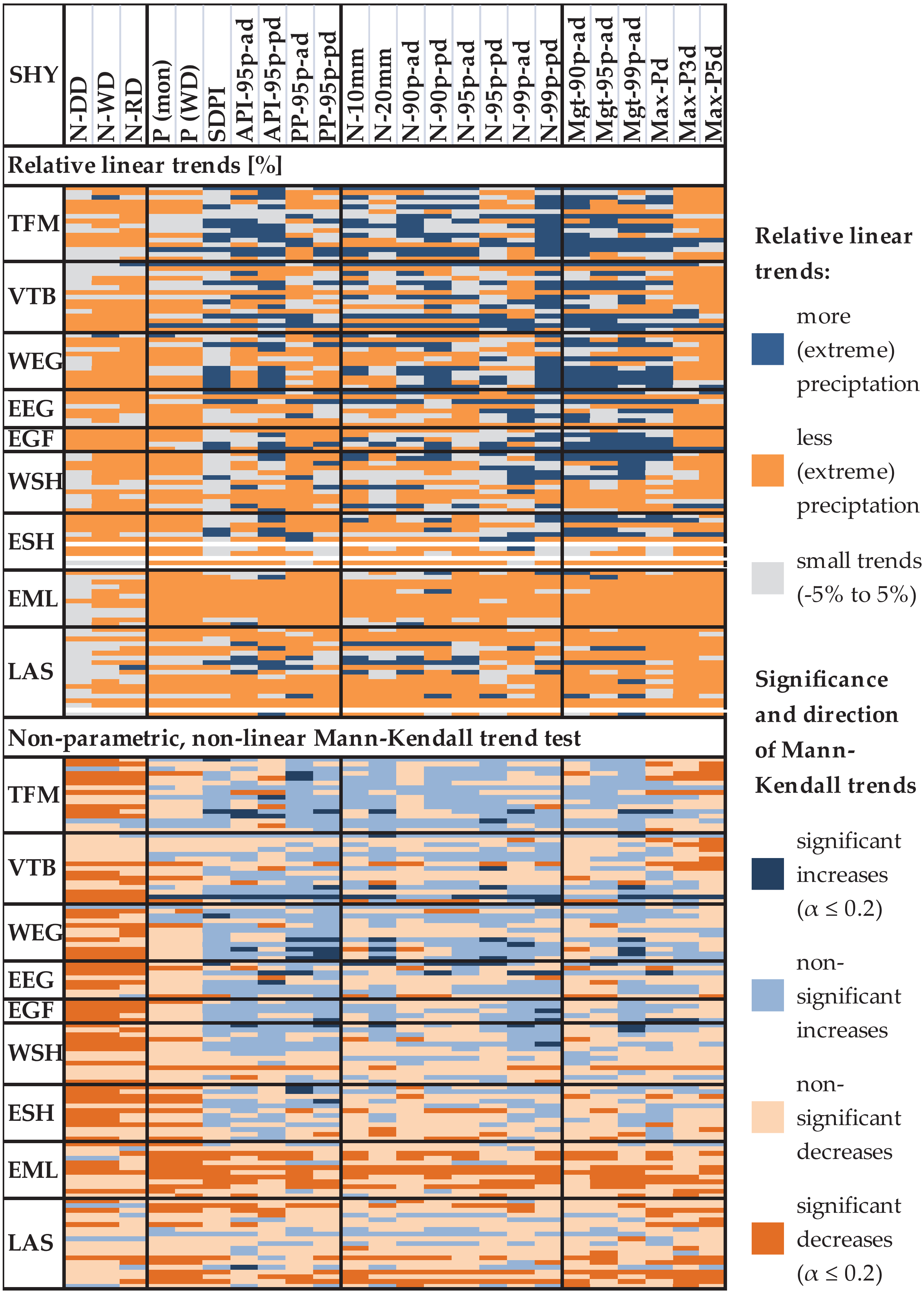


Figure 8.10: Diagram of the summer half year trends of different indicators of daily heavy precipitation extremes expressed as relative linear trends and Mann-Kendall trends for 1951—2000

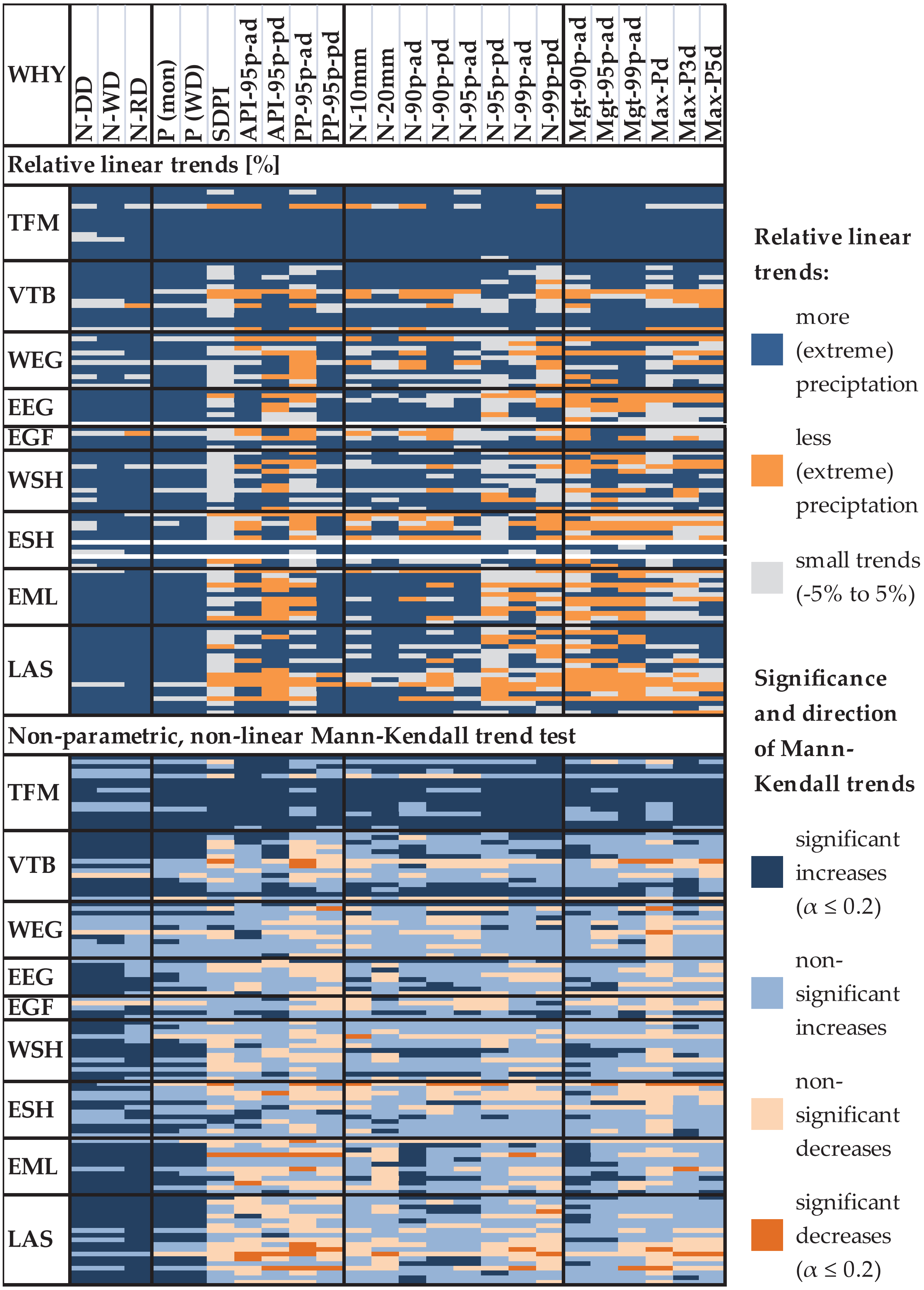


Figure 8.11: Diagram of the winter half year trends of different indicators of daily heavy precipitation extremes expressed as relative linear trends and Mann-Kendall trends for 1951—2000

TFM and VTB for autumn. The spring and autumn trends generally depend quite strongly on the chosen indicator and the connected rarity of heavy precipitation extremes. While precipitation totals decreased in spring, positive HPI trends occurred quite frequently for higher thresholds (20 mm, 99th percentile and Mx-R) as well as for the average precipitation intensity and the percentage of precipitation above the 95th percentile. The autumn trends behave opposite to the spring trends; general precipitation increases are accompanied by frequent decreases in the rarest heavy precipitation events particularly in regions EML and LAS. Similar tendencies of opposite trend directions for average and extreme precipitation indices have been observed on a monthly basis, e.g., for March and May. More often, the changes in moderately extreme heavy precipitation events match the average precipitation changes, while the most extreme events more frequently show opposite trends.

Monthly trends of HPI indicators are displayed in Annex 33. Most indicators of heavy precipitation events indicate decreasing January, July and October trends for the majority of stations, except for region TFM. Despite general precipitation increases in January, frequency and magnitude of heavy precipitation events decreased at a high percentage of stations. In contrast, the decreases in heavy precipitation extremes in July and October match the general precipitation decreases. Just some frequent increases of wet and rain day frequency in October and of average precipitation intensity and shared precipitation above the 95th percentile in July do not fit in. Most frequently significant (Mann-Kendall trend test) are the decreases in the regions VTB, WEG, EEG, EGF and WSH for January, EML and LAS for July as well as WSH and EML for October. March, November and December are characterised by predominantly positive HPI and average precipitation trends. Significant Mann-Kendall trends for March were most frequently observed in the south-western regions TFM and VTB. In November and December, significant increases frequently occurred in all regions, except for the easternmost regions LAS. In August frequent decreases in average and extreme precipitation indices occurred in the regions TFM, WSH and EML, while the other regions, in particular the Erzgebirge regions (WEG, EEG and EGF), were characterised by positive HPI trends. In contrast, the wet day frequency in August increased at the majority of station in all regions, indicating that dry and wet day frequency are unsuitable indicators for changes in heavy precipitation events. In April, May and June frequent decreases in average and moderately extreme precipitation face more frequent increases in the more extreme precipitation indices. Frequent increases in moderately HPI occurred in February and September, while more frequent decreases have been calculated for the more extreme indices (N-20mm, N-99P and Mgt-99P).

9 Conclusions

Average and extreme precipitation characteristics and patterns of nine subregions in Saxony and its surroundings and connected changes within the 20th century were analysed, based on a comprehensive data base of more than 100 official rain gauge stations. Trend analysis with high spatial resolution was possible for the timeframe 1951 to 2006. Prior to 1951, only single stations deliver nearly undisturbed data. Nevertheless, analyses for longer periods starting in 1931 or 1941, respectively, were done for daily 'Heavy Precipitation Indicators' (HPI), based on a less comprehensive data basis. Monthly data were generally available for longer time frames than daily precipitation time series in the "Saxon climate data basis". Thus, secular trend analysis (1901—2006) of drought as well as wet event and period indicators based on monthly precipitation data was possible.

General precipitation characteristics: The regional average and extreme precipitation characteristics strongly depend on the orographic structure of the study area. Regional gradients were observed for many indicators, ranging from high values for precipitation and wet extremes in the mountainous regions in the South-West of the study area (TFM, WEG and EEG) to the lowest values in regions of lower altitudes in the North-East (WSH, ESH, EML and LAS). In contrast, droughts were more frequent and severe in regions with lower precipitation averages. Seasonal and monthly variations in the magnitude of individual indicators were in accordance with the annual precipitation cycle.

Monthly and particularly daily precipitation data strongly depart from normal distribution, while seasonal and annual precipitation totals generally meet the demand of normal distribution, assumed for linear regression and most parametric statistical tests. The departures of median from mean values were largest in March, July, September, October and December and lowest in February, June and November. Trömel (2005) developed a method for trend estimation that accounts for the problem of non-normal distribution in precipitation data, but this method demands considerably more computational effort. A comparison to the standard linear approach showed that linear regression tends to overestimate the trends for non-normal distributed data (Schönwiese and Janoschitz 2005). Within this study, the linear regression approach was used and compared to the results of the non-linear and non-parametric Mann-Kendall trend test. The Mann-Kendall trend test was furthermore applied to estimate the trend's significance. Generally, the linear and Mann-Kendall trends deliver comparable results, with the most significant Mann-Kendall trends for the highest linear changes.

Characterisation of dry and wet extremes: Various indicators quite similarly identified the driest and wettest years, seasons and months within the study area. The years 1904, 1911, 1929, 1942/43, 1951, 1953, 1959, 1962 to 1964, 1972, 1976, 1982, 1991, 1996 and 2003 have been particularly dry within most regions, while 1905, 1915, 1926/27, 1930, 1939, 1941, 1954, 1965/66, 1970, 1974, 1981, 1995 and 2002 have been especially wet. Quite often, an extremely wet or dry year was followed by the other extreme, but there were also dry or wet departures from normal conditions that continue for several months, seasons or years with variable severity. The identified droughts and wet extremes have different characteristics and a different spatial extent. For example the 1982/83 drought has been one of the rare worldwide drought phenomena and occurred during an ENSO event (Glantz et al. 1987). The negative precipitation anomalies of 1962/63 and 1996 were connected with negative temperature anomalies. In contrast, a record-breaking heat wave affected the European continent in summer 2003 (Schär et al. 2004) and led to drought conditions in a number of economic sectors of many European Countries. With increasing global temperatures, drought conditions within the study area will probably be more often connected with high temperature extremes that aggravate the moisture deficits in many sectors. Thus, the purely precipitation based indicators, used in this study, may not accurately reflect the severity of future drought conditions.

Years, identified as particularly dry or wet by the indicators RAI and PNI are quite often affected by dry or wet periods, respectively. Negative departures from normal precipitation seem to be more persistent than positive ones, as decile droughts last considerably longer than decile wet periods. Decile dry and wet periods as well as DP and DPST events often occur simultaneously at a high percentage of stations, whereby the spatial extent of decile droughts is generally higher than for wet periods. This indicates that the occurrence of decile dry periods is predominantly triggered by some larger scale atmospheric processes, while regional small scale precipitation characteristics have a higher influence on the timing of decile wet periods. Large-scale atmospheric circulation pattern seem not only to trigger monthly but also daily precipitation extremes. All dry periods, based on daily precipitation data, showed similar spatial drought pattern, with periods of clustered dry period occurrence as well as high spatial drought coverage simultaneously to decile droughts. Nevertheless, there were also considerable differences in the drought occurrence of different dry period indicators that are due to the different time scales, addressed by individual indicators and the “absolute nature” of the DP and DPST-1mm concepts. Regional differences in dry period duration and frequency were more pronounced for the indicators based on absolute thresholds than for the relative ones (decile indicator and DPST-75%), with less frequent and shorter droughts in the mountainous regions.

The influence of large-scale atmospheric circulation pattern on the timing of long-term drought and wet period conditions was also confirmed by the clustered occurrences of dry and wet periods. Periods of clustered dry period occurrence were 1942—1953, 1958—1964, 1970—1978, 1982—1986 and 1989—1993. Decile wet periods occurred particularly frequent and with high spatial coverage from 1953 to 1958. The spatial coverage of single wet periods was less pronounced in other periods of clustered wet period occurrence, as in 1965—1970 or 1993—1999. Following the annual precipitation cycle, decile dry periods started most often in the months with lower precipitation totals (autumn and winter) and were terminated in the high rainfall summer months. Analogously, decile wet periods often begun in April to June and frequently ended in September to December.

Although the calculation of RAI and PNI included some normalisation procedures, they delivered different frequencies of dry and wet events. For annual data both indicators were slightly biased towards wet extremes, while dry events were more frequent in most months, and seasons. This may be due to changes in precipitation totals with respect to the reference period 1961—1990 and the non-normal distribution of precipitation data. Nevertheless, extremely wet conditions (PNI > 150%, RAI > 4) occurred more frequent than extremely dry (PNI < 50%, RAI < -4) ones in most months and seasons. This is probably due to the lower limitation of precipitation data.

Different percentile calculation approaches for daily precipitation totals were compared. The percentile values of the approach “pd” are considerably larger than those of the method “ad”. This could have a significant influence on the results of trend analysis, when trend results depend on the magnitude and thus severity of wet extremes. On average, the magnitudes of 95P-ad and the 90P-pd were about 10 mm and the one of the 99P-ad about 20 mm, allowing some trend comparisons for the frequency of exceeding absolute (N-10mm and N-20mm) and relative (N-90P, N-95P and N99P) thresholds.

Changes in average precipitation characteristics: The indifferent annual precipitation trends within Saxony, already described by Rapp and Schönwiese (1997) for Eastern Germany and by Hänsel et al. (2005) for Saxony were confirmed. In the long-term trends a West-East-gradient in trend direction and magnitude was observed, with increasing precipitation totals in the southwestern parts (region TFM) of the study area and negative trends in the Eastern and Northern regions (regions EML and LAS).

Highly significant and spatially homogenous trends of opposite direction were observed for the half years. Winter shows positive precipitation trends in all regions, whereas precipitation decreased in the SHY. This summer precipitation decrease was especially high in the agricultural-dominated lowlands in the North of the study area (ESH, EML and LAS). A continuation of this negative summer precipitation trend, would not only increase the irrigation challenge in agriculture, but also lead to changes in the natural vegetation and may enhance problems in the availability and quality of drinking water. Water stress and productivity are major problems for natural as well as agricultural ecosystems, as the precipitation decreases were highest during the 1st vegetation period (April to June). Considerable precipitation increases during summer were only observed for August in the Erzgebirge (WEG, EEG and EGF).

The largest precipitation increases during the WHY occurred in March and November as well as with slightly smaller magnitudes in February and December. A significant precipitation decrease during the WHY was calculated for October in all regions, except for region TFM. Spring and autumn trends were less significant than those of summer and winter for most regions, due to opposite monthly trends.

Significant changes occurred not only in precipitation averages, but also in its distribution, with higher regional differences than for changes in the annual precipitation cycle. The frequency in high precipitation classes increased for the months of the WHY, while the distribution shifted to smaller classes for the summer months. For monthly precipitation distributions, it was shown that mean and median might indicate highly significant opposite precipitation trends, due to non-normal distributed data and highly significant changes in the shape of the distributions.

When looking at the annual precipitation cycles, a distinct redistribution of precipitation becomes visible. Matching the regionally quite homogenous monthly trends the changes in the annual precipitation cycle were very similar for individual regions, with the largest differences for region TFM. The summer maximum has shifted from early to late summer, the autumn minimum from November to October and the winter maximum from January to December. Furthermore, the negative summer and positive winter trends led in some regions, particularly in region TFM, to an equalisation of the summer and winter maximum of the annual precipitation cycle that has been in the past characterised by a distinct summer rain season.

Trends of dry period indicators: In the second half of the 20th century most dry period indicators suggest decreases in drought duration (most pronounced in region TFM), independent from the timescale over which drought conditions were averaged by individual indicators. For the entire century decile droughts indicate slight increases in drought duration, most pronounced in region LAS. The trends of annual drought frequency were less similar for different indicators. Short meteorological dry periods (DP) showed regionally indifferent and comparatively small annual trends, with slightly more negative than positive trends. The annual frequency of decile droughts and days assigned to DPST decreased, while more frequent DPST events have been observed at the majority of stations.

The simultaneous decrease in duration and increase in frequency of DPST events from 1951 to 2006 might give evidence for a more frequent interruption of dry periods by days or periods of above average precipitation in recent times. Significant decreases in the regional coverage of decile droughts during that period confirmed the probably increased influence of small-scale precipitation on drought occurrence and termination.

The monthly and seasonal trends of DP and DPST duration were strongly biased to the month of their termination, as dry period durations are assigned to the month, season or year, respectively, in which the drought is terminated. The frequency of days assigned to a dry period (DP-D, DPST-D) was analysed, to receive more robust information about the extent, to which single months and seasons were affected by drought conditions. The trend results of DP and DP-D frequency were similar, due to the short duration of DP events lasting normally less than a month. In contrast, great differences occurred for the longer lasting DPST droughts.

The SHY is more frequently characterised by trends towards more frequent, severe and longer lasting dry periods than the WHY, matching the summerly precipitation decreases. Opposite tendencies were found for the WHY. Nevertheless, opposite trends of individual indicators are possible due to the different time scales they relate to. Short meteorological dry periods (DP) lasting only a few weeks, for example, increased in frequency and duration during the SHY, while they showed negative trends for the WHY. In contrast, the duration of DPST dry periods lasting several months decreased at a high percentage of stations for both half years, while their frequency increased during the SHY and decreased during the WHY. Seasonal and monthly trends were less robust and significant for longer drought events than for shorter ones. Observed shifts in the timing of drought events (characteristic months of onset and termination) were probably due to changes in average precipitation totals.

Wet period trends: Frequency, duration and regional coverage of decile wet periods declined slightly during the 20th century. The decreases in average duration were least pronounced in regions EML and LAS. Within the second half of the 20th century slight increases in decile wet period duration occurred, while the decreases in frequency were more pronounced than for the entire study period. The onset of decile wet periods became more frequent in July and August and less frequent in April in recent times, while no uniform changes for the characteristic drought termination months were found. The decline in spatial wet period coverage agrees with the results for the spatial extent of decile dry periods in recent decades. Both indicate changes in the large scale atmospheric circulation pattern and a rising influence of small scale convective precipitation events.

Changes in monthly, seasonal and annual dry and wet extremes: Although, most dry period indicators suggested a tendency to less frequent and shorter drought events from 1951 to 2000, the frequency of monthly and annual dry extremes measured by the indicators PNI and RAI increased in 1901—2006. Generally, long-term trends more frequently indicated increasing drought conditions than short-term trends. Dry extremes occurred in recent years very frequently in April and June. In most months and seasons, the trend direction of the frequency of differently severe dry events seems to be quite independent from the severity of events, while the trends of wet extremes depend more strongly on the chosen threshold. Generally, the long-term RAI and PNI trends are more similar for dry than for wet extremes, while short-term trends are very similar independent from the studied extreme. Opposite trends are mainly due to a change in the comparability of RAI and PNI thresholds used to define severe drought conditions. Explanations for the change in threshold comparability at about 1950 are the poor data availability before 1951 (single events have a larger influence on the regional frequencies and magnitudes of the indicators) and the different calculation procedures of the indicators in connection with the timing of the 10 most extreme wet and dry events (the RAI includes the 10 most extreme events into its calculation).

Changes in daily precipitation extremes: The trend results of daily and monthly wet extreme indicators are quite similar and basically match the general precipitation changes, particular for moderately wet extremes. Generally, the trends of moderate extreme heavy precipitation events are more robust and significant than those of the more extreme events, as accidental occurrences or outliers strongly influence the trends of extreme events.

During the SHY HPI, PNI and RAI trends are predominantly negative, while positive trends dominate in the WHY. Nevertheless, the percentage of negative/ positive HPI trends for the SHY/ WHY is lower than compared to average precipitation indices, true for both half years. The seasonal trends are generally less significant than the half year trends. The results of average and extreme precipitation indices are most similar for July, August, October, November and December. But there are also months and seasons for which HPI suggest developments opposite to the trends of average precipitation, particularly for the more extreme events. This applies for January, showing decreases in most HPI, despite general precipitation increases. In contrast, the frequency and magnitude of heavy precipitation events increased at a comparatively high percentage of stations from April to June, although those months are characterised by distinct precipitation decreases.

Months and regions with most significant changes: The RAI and PNI trends for dry extremes were temporarily most representative in March, April, May, November and December, while they were least temporally representative in February and September. The temporal representativeness of wet extreme trends was higher than the one of dry extremes for most months and seasons. For both half years, the summer season, March, June, July, October and December it was particularly high.

Most drought indicators showed the most significant increases in drought frequency, severity and/ or duration for May and to a slightly less extent also for August. In contrast, March, November and December are the months that most often became less drought-affected, but showed the regionally most homogenous and most frequently significant increases in HPI. Nevertheless, significant HPI trends were considerably less frequently observed in the Northeastern regions ESH, EML and LAS. Those results are in accordance with the general precipitation trends, while the distinct precipitation decreases in October did not seem to further aggravate the drought conditions, particularly true for indicators of longer lasting dry periods. For April and June the drought indicators gave variable results. While the frequency of severe drought events frequently increased in April and decreased in June, duration and frequency of dry periods decreased in April and increased in June. Decreases in HPI were most pronounced in February, July and October, except for region TFM. During August HPI indicate significant increases in frequency and severity of heavy precipitation events for the Erzgebirge (WEG, EEG).

Regionally, the increases in drought, frequency, intensity and duration were most pronounced in the north-eastern regions EML and LAS, matching the strong precipitation decreases during the SHY. Analogously, the decreases in HPI, PNI and RAI were most significant in those regions. In contrast, region TFM, characterised by the strongest precipitation increases, became less drought affected, but more affected by heavy precipitation events and wet anomalies in most months and seasons.

Spatial and temporal representativeness of trends: The natural variability of precipitation is reflected by the moving 30-year-trends. Although those short-term trends were highly variable in time and space, some trend pattern became visible in the moving 30-year trend analysis, particularly pronounced for monthly trends. The trends were of same direction for the majority of stations and trend reversals occurred quite simultaneously in different regions for most months, suggesting a high spatial representativeness of trends. Those trend patterns indicate a high influence of large-scale precipitation triggers on average and extreme precipitation changes. Highly temporal persistent positive short-term trends of precipitation totals were observed for March, November and December, the months with the most significant long-term trends, while negative trends were of high persistence in May and October. The regionally most homogenous HPI developments with same trend directions and timing of trend reversal in most regions were observed in February, July, October, November and December, quite independent from the chosen threshold and the connected rarity of the events. Generally, the trends of the more extreme HPI are temporarily and spatially more variable and thus less representative than those of moderate extreme events. In August the 30-year precipitation trends were most heterogeneous, indicating a high influence of small-scale and local precipitation characteristics (convective precipitation) on the trends.

When looking at extreme drought events that are especially long lasting or severe or both, it becomes apparent that 50 years is far from being sufficient for reliable trend analysis. The same applies for extreme heavy precipitation events. Unfortunately there are only very few stations with long homogenous precipitation records. An accurate analysis of the spatial drought characteristics and extreme HPI trends is therefore quite difficult.

The suitability of individual drought indicators has to be checked for the particular application area. Short-time meteorological dry periods (DP), particularly those during the vegetation period, might be of high relevance for agricultural studies, while long-term droughts (e.g., decile dry periods) are more relevant for hydrological applications. DSPT dry periods stand in between, as their threshold is adjustable to the particular application area. Nevertheless, there are various indicators, designed especially for the analysis of agricultural or hydrological drought, respectively.

Spatial pattern of many daily and monthly (extreme) precipitation and drought indicators as well as their connected trends indicate a high influence of large-scale atmospheric circulation pattern on the precipitation characteristics and trends within the study area. Analyses of the nature and changes of those atmospheric circulation patterns would be very valuable. Probably atmospheric circulation indices like NAO or NAM could explain partly the observed trends and patterns. It has been already detected that NAO and NAM changes are influencing the westerlies in the Northern Hemisphere (IPCC 2007). The westerlies themselves alter the flow from oceans to continents and are a major cause of changes in winter storm tracks and related patterns of precipitation and temperature anomalies.

Further analysis of drought indicators incorporating other climate variables should be done, as observed and projected temperature increases may aggravate existing drought conditions. Meteorological dry period indicators, evaluating just the precipitation deficits, might underestimate the severity of drought events accompanied by temperature extremes. Nevertheless, the year 2003, characterised by an extreme heat wave, was also identified as one of the most extreme dry events by the purely precipitation based drought indicators.

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Figures

Tables

Abbreviations

Abbreviation	Description
90P	90th percentile of daily precipitation
95P	95th percentile of daily precipitation
99P	99th percentile of daily precipitation
ad	approach of percentile calculation using all non-missing days
Ann	Annual
API-95P	Average precipitation intensity on days with precipitation above 95P
Apr	April
Aug	August
Aut	autumn
Av	Average
AvD-DWP	Average duration of decile wet periods
DD	Decile dry periods
Dec	December
DJF	winter months December, January and February
DP	meteorological dry periods
DPST	Concept of Dry periods with sliding thresholds
EEG	Eastern Erzgebirge
EGF	Erzgebirge Foreland
EML	Elbe-Mulde Lowlands
ENSO	El Niño-Southern Oscillation
ESH	Eastern Saxon Hilly Country
Feb	February
HPI	Heavy precipitation indices
IPCC	Intergovernmental Panel on Climate Change
Jan	January
JJA	summer months June, July and August
Jul	July
Jun	June
KS-test	Kolmogorov-Smirnov test
KW-test	Kruskal Wallis test

Abbreviation	Description
LAS	Lausitz and Spreewald
Mar	March
Mgt	Magnitude
Mgt-90P	Magnitude of the 90th percentile of daily precipitation
Mgt-95P	Magnitude of the 95th percentile of daily precipitation
Mgt-99P	Magnitude of the 99th percentile of daily precipitation
Mx	Maximal
MxD-DWP	Maximum duration of decile wet periods
Mx-PNI	Greatest PNI value
Mx-R3D	Greatest 3-day precipitation total
Mx-R5D	Greatest 5-day precipitation total
Mx-RAI	Greatest RAI value
Mx-RD	Maximum daily precipitation total
N	Number
N-10mm	Number of events with precipitation greater than 10 mm daily rainfall
N-20mm	Number of events with precipitation greater than 10 mm daily rainfall
N-90P	Number of events with precipitation greater than the 90th percentile of daily precipitation
N-95P	Number of events with precipitation greater than the 95th percentile of daily precipitation
N-99P	Number of events with precipitation greater than the 99th percentile of daily precipitation
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
ND	normal distribution
N-DD	Number of dry days ($P_d \leq 1$ mm)
N-DWP	Number of decile wet periods
Nov	November
N-PNI-…	Relative frequency of stations with a PNI above a certain threshold
N-RAI-…	Relative frequency of stations with a RAI above a certain threshold
N-RD	Number of rain days ($P_d \geq 2$ mm)
N-WD	Number of wet days ($P_d > 1$ mm)
Oct	October
P	percentile
pd	approach of percentile calculation using only days with precipitation different from zero
PDSI	Palmer Drought Severity Index
PNI	Percent of Normal Indicator
ppmv	parts per million by volume
R	precipitation

Abbreviation	Description
R-95P	Percentage of total precipitation from events above 95P
RAI	Rainfall Anomaly Index
RC-DWP	Percentage of stations affected by a decile wet period
R-WD	Precipitation total of wet days
SAM	Southern Annular Mode
SDPI	Simple daily precipitation intensity index
Sep	September
SHY	summer half year
Spr	spring
SRES	IPCC Special Report on Emission Scenarios
Sum	summer
TFM	Thuringian-Franconian Mountains
VTB	Vogtland and Thuringian Basin
WEG	Western Erzgebirge
WHY	winter half year
Win	winter
WSH	Western Saxon Hilly Country

Abstract

Many recent examples have shown the vulnerability of human society towards climate extremes such as droughts, floods and storms. That is why it is particularly important to analyse possible changes in the frequency and intensity of such phenomena.

The study area of Saxony and its surroundings is situated at the interface of dominantly oceanic versus continental climate regimes. Therefore, its precipitation trends are considerably different from the more western parts of Germany, with indifferent annual precipitation trends. Changes of regional precipitation patterns as well as daily and monthly rainfall extremes, were analysed for different timeframes (e.g., 1901—2006 and 1951—2000), including an estimation of the time dependence of the analysis results. Besides station based trends, regional analyses were performed for nine regions with similar precipitation characteristics.

Shifts in the annual precipitation cycle occurred, due to reversed rainfall trends in the individual months. For instance, the winter precipitation maximum increased and shifted from January to December, while the summer maximum decreased and shifted from early to late summer. Furthermore, changes in the frequency distribution of monthly rainfall totals became visible with shifts to smaller classes during the SHY and inverse shifts during the WHY.

Various drought indices were calculated to characterise Saxon droughts and to detect regional changes, e.g., in drought frequency, intensity and duration. Recent changes in wet extremes were evaluated, using different heavy precipitation and wet period indicators. By comparing individual indicators, the major Saxon drought and wet years were identified. Dry and wet periods, respectively, often occur simultaneously at most stations and clustered in time, indicating a high dependence on large-scale atmospheric circulation pattern.

The trends of wet and dry extremes match the general precipitation trends for most months and seasons, with increasing drought conditions in the SHY and

increasing wet extremes in the WHY. Indicators of more extreme and thus less frequent events might also indicate opposite trends, e.g., slight increases in heavy precipitation events in summer, although those trends are generally less robust and significant. The dependence of trends on the time-scale, individual indicators are addressing, is higher for dry rather than for wet extremes. While shorter dry periods increased in frequency and duration in the SHY, the persistence of longer events decreased in the second part of the 20^{th} century. The regional coverage of decile droughts and wet periods declined in recent decades, indicating an increasing influence of small scale precipitation pattern. Changes in daily and monthly wet extremes are very similar, particularly for indicators of moderate extremes. Many indicators show a spatial gradient from SW to NE in the magnitude of indicators and related trends. North-eastern regions were more frequently and severely affected by droughts, while increases in wet extremes were most pronounced in the south-western parts of the study area.

Trend analysis of extreme drought or heavy precipitation events showed that timeframes of 50 years are far from being sufficient for reliable trend analysis, as the natural variability of climate is very large. Analysis of longer time-series revealed some similarities, but also some discrepancies to the results of 1951—2006.

Zusammenfassung

Das Schadpotential extremer Klimaereignisse für die menschliche Gesellschaft, wurde in den letzen Jahren durch viele Beispiele eindrucksvoll belegt. Die Analyse von Veränderungen in der Häufigkeit und Intensität solcher Ereignisse ist daher von herausragender Bedeutung.

Das Untersuchungsgebiet Sachsen liegt im Übergangsbereich überwiegend ozeanisch und kontinental geprägter Klimate. Daher unterscheiden sich die Niederschlagstrends deutlich von den für das westliche Deutschland beobachteten Entwicklungen. Sie zeigen räumlich uneinheitliche und zumeist kleine jährliche Veränderungen. Verschiebungen in den regionalen Niederschlagsmustern sowie den täglichen und monatlichen Niederschlagsextremen wurden für verschiedene Zeiträume (z.B. 1901—2006 und 1951—2000) untersucht und verglichen. Neben stationsbasierten Untersuchungen erfolgten auch regionale Analysen für die identifizierten neun Regionen ähnlicher Niederschlagscharakteristik.

Entgegen gerichtete Trends einzelner Monate führten zu Veränderungen im Jahresgang des Niederschlags. So verschoben sich die Winter- und Sommerniederschlagsmaxima vom Januar in den Dezember und vom Früh- in den Spätsommer. Die Niederschlagsveränderungen spiegeln sich auch in den Häufigkeitsverteilungen des Monatsniederschlags wieder, kleine Niederschlagklassen wurden im SHJ häufiger und im WHJ weniger häufig belegt.

Sächsische Dürrecharakteristika und -trends wurden mittels verschiedener Dürreindikatoren untersucht, während die Bewertung von Veränderungen in den „Nassextremen“ anhand diverser Starkniederschlags- und Nasszeitindikatoren erfolgte. Die bedeutendsten Trocken- und Nassjahre wurden über den Vergleich der Ergebnisse verschiedener Indikatoren ermittelt. Trocken- und Nassperioden treten häufig in weiten Bereichen des Untersuchungsgebietes gleichzeitig und in bestimmten Zeitabschnitten gehäuft auf, was auf eine Abhängigkeit von großräumigen atmosphärischen Zirkulationsmustern hinweist.

Die Trends trockener und nasser Niederschlagsextreme folgen häufig den allgemeinen Niederschlagsveränderungen, mit einem Anstieg von Dürrezuständen im SHJ und zunehmenden Nassextremen im WHJ. Entgegen gerichtete Trends, wie leichte Starkniederschlagszunahmen im Sommer, traten im Wesentlichen für Indikatoren extremerer und folglich besonders seltener Ereignisse auf. Sie sind im Allgemeinen jedoch weniger robust und signifikant. Die Trends trockener Niederschlagsextreme hängen stärker von den Zeitskalen, die durch die einzelnen Indikatoren abgedeckt werden, ab, als die von Nassextremen. Während die Häufigkeit und Andauer kurzer meteorologischer Trockenperioden im SHJ in der zweiten Hälfte des 20. Jahrhunderts zunahm, verringerte sich die Persistenz langer Trockenzeiten. Die Abnahme in der räumlichen Deckung von Dezil-Nass- und -Trockenperioden in den letzen Jahrzehnten deutet auf eine zunehmende Bedeutung kleinräumiger Niederschlagsmuster hin. Tägliche und monatliche Nassextreme zeigen sehr ähnliche Trends, insbesondere für Indikatoren gemäßigter Extreme. Viele Indikatoren weisen in ihrer Größe sowie den Trends einen räumlichen Gradienten von SW nach NO auf. Nordöstliche Regionen werden häufiger und schwerwiegender von Dürren betroffen, während die Anstiege in den Nassextremen in den südwestlichen Gebieten des Untersuchungsgebietes am deutlichsten ausfallen.

Die Analyse besonders extremer Dürren und Starkniederschlagsereignisse zeigte, dass aufgrund der großen natürlichen Klimavariabilität, Zeiträume von 50 Jahren unzureichend für eine zuverlässige Trendanalyse solch extremer Ereignisse sind. Die Untersuchung längerer Zeiträume ergab einige Ähnlichkeiten in den Trendmustern im Vergleich zum Zeitintervall 1951—2006, jedoch auch einige bedeutende Abweichungen.

Sponsored by the Scholarship Programme of the German Federal Environmental Foundation

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Acknowledgements

I wish to express my gratitude to ‘Deutsche Bundesstiftung Umwelt’ DBU for financing my PhD-project and giving a lot of additional professional and human support during three years of intense work.

Many thanks also go to the Saxon State Agency for Environment, the TU Dresden and the German Meteorological Survey (DWD) for contributing the data and giving useful scientific advice.

Jörg Matschullat being the supervisor of doctoral thesis supported me wherever possible and helped a lot in improving my English during the last years. Thank you very much for everything!

My family in particular my parents Heike and Rolf and my husband Mario were backing me all the way. Without you the work would probably not have been that smooth. I am very glad that I can always count on you.

My son Jan, born in the third year of my doctorate, initiated a reorganization of my work style that became much more effective. The countless golden hours with him gave me new energy to finalise my dissertation and I hope we will enjoy a lot more.

Thanks to everybody working together with me during the last years. Thank you Andreas Hoy for providing the pictures for the front page and in particular for your critical reading of the manuscript. It helped a lot!

Last but not least I want to thank the reviewers Prof. Bernhofer and Prof. Ulbrich for their advices and recommendations that helped to improve the scientific quality of the work.

Annex (digital on enclosed CD-Rom)

Annex 1: List of rain gauge and climate stations

Annex 2: Dependence of Pearson product moment correlation coefficients magnitudes on the distance of station in individual months, timeframe 1951—2000

Annex 3: Correlation matrices for single months using the Pearson product moment correlation coefficient, timeframe 1951—2000

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Annex 9: Monthly and seasonal Rainfall Anomaly Index RAI (Mean, maximum and minimum RAI of 130 stations); timeframe: 1900—2006

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