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

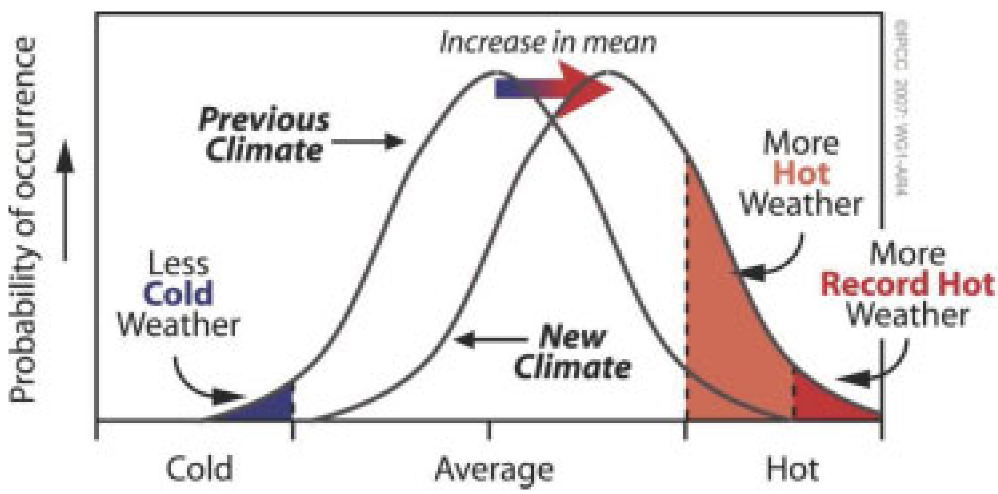

Figure 2.1: Scheme of the effect of mean temperature increases on extreme temperatures, for a normal temperature distribution (from IPCC 2007: Box TS.5).

focused on standard and robust statistics that describe moderately extreme events (between the 1^{st} and 10^{th} 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.