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Reconstructions of Droughts in Germany since 1500

Rüdiger Glaser[1], Michael Kahle[1]

[1]Physical Geography, Institute for Socio-Environmental Studies and Geography, University of Freiburg, 79098, Germany

Correspondence to: Rüdiger Glaser (ruediger.glaser@geographie.uni-freiburg.de)

Abstract. The present article deals with the reconstruction of drought time series in Germany since 1500. The reconstructions are based on written records from the historical climate and environmental database tambora.org, early and official instrument data as well as precipitation and temperature indices.

From the historical descriptions of the weather climatic processes and their effects and consequences for the environment and society, action paths and drought categories are derived. Furthermore, a historical precipitation index (HPI) is calculated and correlated with the SPI index. These are correlated and quantified in a rating scheme with modern rainfall indices and recent drought categories. Finally, a Historical Drought Index (HDI) and a Historical Wet Index (HWI) derived from the hygric indices are presented.

On this basis, the long-term development of dryness and drought and significant accumulations and extremes in Germany since 1500 are discussed.

Keywords: Historical Wet Index, Drought, SPI, Pathways

1 Introduction

Exceptional dry periods and long lasting drought events such as 2018, 2015, 2010 and 2003 have occurred in central Europe in recent years. The comparatively rapid consequence raises the question of how far this is another indicator of climate change. The consequential damages are in the billions, whereby primarily agriculture and forestry, but also water management is affected. More and more, the focus is set on the negative consequences onto environment and society, regarding health effects likewise heat stress, or the negative consequences on infrastructure and transportation (Kreibich et al. 2019, Erfurt et al. 2019, Blauhut et al. 2015a , b , 2016, Bachmair et al., 2016, Stagge et al., 2013, 2015, Van Dijk et al., 2013).

In addition to many climatological, ecological and social specifications, long-term reconstructions are necessary for comprehensive risk assessments. They contribute significantly to answering questions about long-term trends, accumulations and recurrence times.

Droughts are generally referred to as a period of extremely dry weather that persists long enough to cause a severe deficit in the water balance, which in turn causes environmental and social impacts and damage (Wilhite & Glantz 1985, Glaser & Erfurt 2019). From a statistical point of view, a drought is an exceptional event with a rare recurrence probability (Benestad 2003). Basically, according to a widely used scheme, droughts will be subdivided into four types that reflect the time course: The meteorological drought describes a period of considerable precipitation deficit, usually in comparison with a comparable period. High air temperatures and wind speeds, more intensive solar radiation and freedom from clouds can aggravate the precipitation deficit (Wilhite & Glantz 1985). With continued duration, restrictions on the amount of plant-available soil water and initial effects on plant growth as well as harvest yields development may occur. In this case, it is named an agricultural drought (Bernhofer et al., 2015). If the drought continues to progress, reduced surface runoff, sinking water

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and water levels and ultimately sinking groundwater levels, the so-called hydrological droughts, occurs. At extremely low groundwater levels or baseline flows, it is called a groundwater drought. The term Socio-economic drought is used, when it comes to impacts on people and the environment. The degree of severity depends on the needs of the people, but also on the equipment, the adjustment options and the resilience.

Droughts can be defined according to very different criteria, which corresponds to the large number of indices. They differ in the type of input data, the temporal and spatial coverage and the consequences for different sectors. The input data used for the meteorological drought are temperature and precipitation data. Assessments of hydrological droughts are based on gauging data, groundwater levels and runoff. The temporal reference ranges from days over weeks and months to years (Bernhofer et al., 2015), the spatial relationship also varies according to the question.

Common drought indices include the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI) and the Palmer Drought Severity Index (PDSI). In the US, the PDSI is the most common drought index used and also the basis for the US Drought Monitor (Palmer 1965 , McKee et al 1993, Vicente-Serrano et al 2010, Zargar et al 2011, Svoboda et al 2012). In the German Drought Monitor (Dürremonitor Deutschland), the current monthly status of the soil is represented in five dry classes (Zink et al 2016, DWD 2019). Beyond the indices, the consequences are also taken into account when assessing drought (Stahl et al., 2016).

The aim of the present contribution is the reconstruction of long-term drought time series in Germany since 1500 on the basis of written records. For this purpose, a rating scheme is to be developed which makes it possible to correlate recent parameters and criteria of drought valuations with historical ones. For this purpose, various drought indices and drought categories are developed and evaluated. The long-term development should be evaluated, in particular the question to what extent the current developments differ from the previous phases.

2 Data

The analysis is based on the comprehensive data sets on weather, weather and climate as well as their consequences on the environment and society in Germany, as they are available in the historical climate and environmental database tambora.org (tambora.org, Riemann et al 2016, Glaser et al. 2018). The approximately 280,000 records relevant to Germany are written documents taken from weather diaries, chronicles, pamphlets, official reports and newspaper reports. These are supplemented by other media such as flood marks, hunger stones, pictures and lyrics. The information covers the German area well (Fig.1). All written sources were processed according to the methods used in historical climatology (Pfister 1999, Brazdil et al., 2005, Glaser 2013).

[Fig. 1: Spatial distribution of information in tambora.org]

The information in tambora.org is coded, especially the spatial, temporal and content aspects are classified into numerical codes. The information relevant for the analysis of dryness and drought events, in particular the temperature and precipitation information are completely available from 1500 onwards as seven-level monthly indices (Fig. 2). In addition, hydrological extremes, in particular high and low water as well as phenological hints are available. In addition to the drought events there are many descriptions of the impacts on the environment and society. In addition to the coded events, the original text quotes are also included in the database so that the overall context and the coding can be traced at any time. The sources of drought are extremely varied and differentiated. For example, in the 123 sources for the Drought Year 1540, 41% of the data refer to agriculture, 17% to water, 11% to health, 10% to forest fires, 8% to soil and 8% to the environment and ecosystem. Basically, outstanding drought events are documented by particularly many and differentiated sources. Particularly well-documented events of the century include 1540, 1503 and 1534, 1615 and 1616, 1669 and 1684, and 1718 and 1719, 1834, 1842, 1865 and 1893, 1921, 1949, 1959, 1976, 2003 and 2018.

In addition, from 1881 onward the official precipitation data for Germany can be used. From 1800 onward early precipitation measurements and derived drought indices are available (Erfurt et al. 2019) as well as the revised and supplemented precipitation indices from 1500 to 1995 (Glaser 2013, Glaser & Kahle 2019).

[Fig. 2: Summary of the monthly precipitation index (PI) for Germany from AD 1500-2018]

3 Methods

Numerous studies on droughts with an explicitly historical perspective have been presented in recent years, for example by Gil-Guirado et al (2019), Brazdil et al. (2018, 2019), Erfurt et al. (2019). A wide range of content and methodological aspects was taken up and implemented. The spectrum ranges from analyzes of outstanding individual years (Wetter et al., 2014), the derivation of regional time series in different climatic zones (Noone et al 2017, Kiss 2017, Dobrovolný et al., 2018, Nash et al., 2019), to the focus on effects (Glaser et al., 2017).

The study presented here examines the extent to which the seven-level historical index scale can be linked to existing, recent quantitative drought classifications. It will also be analyzed to what extent a quantitative estimate of the historical reconstructions can be obtained and, if a comparison with modern developments is possible. The starting point are the parameters and criteria used in the Drought Severity Classification (NDCM) 2018) or the Drought Index of the German Weather Service (DWD 2018). These include drought indices derived from measured data, such as the SPI, the SPEI and the Palmer Drought Severity Index, as well as the assessment of the severity of droughts in the form of drought categories. In addition, effects and consequences are described in short blocks of text. These follow the criteria used in the general drought classifications of an agricultural, then hydrological and finally socio-economic drought. These descriptions and categories include duration information.

In the further analysis, the modern descriptions and drought categories are to be related to the historical ones. For this purpose, pathways and corresponding drought categories are derived from the historical sources. Likewise a historical precipitation index (HPI).

Determination of modern SPI and mapping of recent drought categories

The modern SPI1-SPI12 was calculated from the official precipitation values for Germany 1881 - 2018 (Tab.1, first column). The drought categories and the characterization of the droughts as well as the duration and the description of the consequences were taken over from the scheme of the DWD (DWD 2018).

Derivation of historical pathways and drought categories

The descriptions of the consequences and effects of drought on the environment and society used in the historical sources follow a structure very similar to recent approaches (Freiburger Zeitung 1834, Pfaff 1846, Brooks & Gkasspole 1922, DWD 1947a, b, Dürr 1986, Glaser et al 2016, Brazdil et al 2016, Nash et al 2019, Erfurt et al 2019). With the duration of the precipitation deficit, cascade-like effects

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first appear in the agricultural, then the hydrological and finally the socio-economic droughts, as they are also expressed in the drought definitions.

These time- and intensity-related cascade effects can be derived from the historical sources as characteristic pathways: First, the absence of rain and first signs of dryness and a beginning drought in historical sources are usually described very precisely. Often these are provided with time information, especially duration, beginning and end of drought. Very often information is given on the phenological phases, in particular the prematurity of flowering, but also the field cropping and harvest dates. With increasing drought, the consequences for agriculture, in particular crop damage in the main crops and failures in rain-sensitive horticultural products and hay, are described. As the drought progresses, both the number of descriptions and the differentiation of messages increase: emergency slaughter for lack of food and evidence of emergency crops prove the increase. Descriptions of the water balance situation are added at this stage: low water levels in waterbodies, subsidence of spring discharges, drying up of small wells. Effects on the environment such as forest fires, fish dying, algae blooms and various forms of soil degradation such as deflation and dry cracks complete the picture. The explanations are now also supplemented by indications of problems with the infrastructure, in particular the problems with the low water levels and the mill operation. Also, health consequences such as heat stress and heat death as well as increased mortality from the outbreak of epidemics, often due to poor water quality, are reported. Harvest losses lead to price increases and with further increase to hunger. Religious rites such as prayer services for rain or processions, but also official measures such as water rationing are taken. If the drought persists, the conditions described become more acute. In the historical context, especially after famine crises and epidemics, there are social excesses such as looting, robbery, persecution of minorities and excluded groups of people as well as emigration and migration (Glaser et al., 2017, 2018). Fortunately, these are lacking in the modern context in Europe after 1950. However, the extreme droughts were also accompanied by protests and strikes as a result of the special circumstances in the post-war period 1947 and 1949 (DWD 1947a, Nees & Kehrer 2002, Erfurt et al., 2019, Brazdil et al., 2016).

These cascade effects over the duration of the drought and dryness, which also follow the classical definitions of drought, are understood as pathways and their grades can be classified as drought categories. These are shown in the last column of Table 1 (Table 1).

Because the pathways and drought categories are very similar to descriptions of the consequences and implications of modern classifications, it is possible to parallelize them on a hermeneutical basis.

Derivation of the Historical Precipitation Index (HPI)

In order to put the drought and drought -related patterns in the overall framework of hygric development, the next step was to include the positive hygric indices. These represent humid and wet conditions at month scale.

The derivation of the historical precipitation index (HPI) from the monthly precipitation indices (PI) - including the positive deviations - is analogous to the SPI as the sum of the corresponding number of months of the period 1881-1996. The strength of the statistical relationship and its shape are shown in Figure 3.

[Fig. 3: Strength and shape of the relationship between SPI and HPI 1881-1996]

The results show a very high correlation of 0.65 to 0.74 between SPI and HPI!

If one compares the accumulated values, then a factor dependent on the number of months results (Fig. 4)..

https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

[Fig. 4: Duration and scale factors of the relationship between SPI and HPI]

The calculation of the HPI class limits is done from the SPI class limits according to the formula:

$$HPI_i = SPI_i \cdot i^{\frac{1}{\sqrt{3}}}$$

The synopsis of recent SPI, drought categories, duration, recent descriptions and the HPI as well as the description of the historical consequences and impacts are summarized in Table 1 (Tab 1).

Tab. 1.: Synopsis of SPI and HPI

SPI	**Drought-categories**	**Duration months**	**Recent descriptions of the effects and consequences as well as the duration**	**HPI** (Historical Precipitation Index)	**Historical descriptions of effects and duration**
-0.1 to -0.99 (SPI1, SPI2)	almost normal (slight dryness) D0	1-2	short-term dryness	0 to -1.5 (HPI1, HPI2)	low rainfall, heat and drought, possible first consequences for agriculture and yields
-1.0 to -1.49 (SPI1, SPI2)	moderate drought D1	1-2	meteorological drought: one to two months drier than usual	-1.5 to -2.5 (HPI1, HPI2)	lower crop impact on main crops, failures in rain-sensitive horticultural products and hay, better wine quality
-1.5 to -1.99 (SPI2 - SPI4)	severe drought D2	2-4	agricultural drought: two months and longer dry, crop losses	-2.5 to -4.5 (HPI2 - HPI4)	crop losses on main crops, emergency slaughter for lack of food, prematurity phenological phases, drying up springs, low water levels, mill arrest, forest fires, problems with water supply, heat deaths, measures of the authorities, price increases, hunger, religious rites
-2.0 to -2.99 (SPI4-SPI10)	extreme drought D3	4-10	hydrological drought: from four months, groundwater and level affected	-4.5 to -12 (HPI4 - HPI10)	crop failures, emergency slaughterings, strong premature phenological phases forest fires, fish dying, algal blooms, soil erosion drying of springs and wells, low water levels of large rivers, hunger stones, heat deaths, epidemics, price increases and speculation, measures of the authorities, hunger, religious rites, increasing irrational explanations
-3.0 to -4.0 (SPI10-SPI12)	extra-ordinary drought D4	> 10	socio-economic drought: from one year, water shortage slows down producing economy	-12 to -36 (HPI10 - HPI12)	...begging, moving about, searching for food, food substitution, robbery, plunder, murder, emigration and emigration, social excesses (Century-events)

https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

Derivation of SPI time series from 1500

Since the drought arises over the intensity and duration of the precipitation deficit and are used for the evaluation of SPIs of different duration (see Table 1, first column), in a further step the monthly precipitation index (PI) from 1500 were summed up to HPIs 1-12 and transformed into SPIs (Fig. 5). Shown are SPI3, SPI6 and SPI12.

[Fig. 5: Historical SPI3, SPI6 and SPI12 for Germany since 1500]

Derivation of the Historical Drought Index (HDI) and comparison with the Modern Drought Index (MDI) from 1881

In a next step, for the determination of the Historical Drought Index (HDI), the classes defined in Table 1 were stepwise interpolated linearly. These are shown in Figure 6 and compared with the MDI of the DWD for the calibration phase 1881-1996. The correlation of r = 0.478 underlines the similarity or strength of the relationship between the two variables.

[Fig. 6: Historical Drought Index (HDI) vs Modern Drought Index (MDI)]

This approach was used to calculate the last 500 years. To include not only dryness and drought aspects humidity has also taken into account for the analysis by including the positive hygric indices as a Historical Wet Index (HWI). Its derivation was analogous to the class boundaries of the drought categories. The dominating effects of the HDI and the HWI are combined into the Historical Humidity Index (HHI). The monthly results are shown in Figure 6, along with the frequency-filtered signals for 1 and 5 years (Fig.7).

[Fig.7: Historical Humidity Index (HHI) for Germany from 1500]

4 Results and discussion

Documentary Data

The written sources on which the analyzes are based and the derived seven-step monthly precipitation indices (PI) for Germany, allow differentiated statements about the climatic causes and the development of dryness and droughts in Germany since 1500. The consequences and impacts on the environment and society can also be reconstructed very well. The information of the droughts is differentiated and very detailed. In many cases information is available about the temporal structure, in particular the onset, the end and the development. They are thus similar in content to other Central European historical sources (Pfister 1999, Brazdil et al., 2019).

Pathways

The contentual differentiation of the source material enables in particular to derive pathways from the causes of dryness and drought events and their consequences and impacts. These are very strongly coupled with the intensity and duration of the precipitation deficiency. The agrarian, then

https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

the hydrological and finally the socio-economic consequences are presented in a progressing cascade. Structurally they correspond to today's drought definitions and drought classification. The descriptions of impacts and consequences and the derived pathways of historical events are very similar to recent events (Erfurt et al 2019, Blauhut et al. 2016, Glaser et al. 2016, 2017, 2018, Brazdil et al. 2016, 2019 or Nash et al 2019) so that a parallelization is possible.

These statements apply to the pathways itself, but not to adaptation manners or resilience. Obviously, over the centuries, these have become due to the social structure, the assets, technical possibilities and thus the adaptation (Glaser et al. 2018, Camenisch & Rohr 2018, Camenisch et al. 2014). In the historical context, for example, water-driven mills play a key role in food security. Due to lacking water, horse mills or hand mills were set into operation. In today's context, on the other hand, the lower energy production of hydropower plants, or the shutdown of nuclear power plants at low water or at high water temperatures plays a major role (DWD 1947a,b, Loßnitzer 1947, BNN 1947a,b, DWD 1949a,b, BNN 1949a,b, Erfurt et al. 2019). Also within the historical period, i.e. before the establishment of the official measuring network from 1881, the social and technical possibilities and structures changed. From 1800 onward the dominant agricultural-feudal structures were gradually replaced by the industrial revolution. There were also new possibilities for adaptation: such as an improved infrastructure, better technical equipment such as pumps, more expertise and better hygiene and social welfare measures. The striking emigration waves of the 19th century from Germany to North America were also repeatedly triggered by drought events (Glaser et al 2017). Added to this were innovations such as the advent of the insurance industry (Kiermayr-Bühn 2009). Also the reactions of institutions in the modern age - understood as governance - can be seen in this context. Examples are the DWD's establishment of the heat warning system in 2005 as a result of the extreme summer of 2003 (Matzarakis 2016) with its unexpectedly large number of heat deaths or the implementation of a new 2019 drought index after the extreme year of 2018 (DWD 2019).

Nonetheless, there are many similarities between the recent and historical pathways that justify parallelizing past and historical drought categories through the cascade effects. This combination of hermeneutic criteria with empirically derived indices represents an intrinsic and unique value.

Overall, a stringent evaluation scheme was derived, which comes very close to the current assessments of drought events such as the NDMC (2018) or the German Weather Service (DWD 2018, 2019).

Outstanding single years

The comprehensive data collections in tambora.org also enable to identify outstanding and correspondingly well-documented events of the centuries. These are 1540, 1503 and 1534; 1615 and 1616, the striking sequence 1630-1635, 1669 and 1684, and 1718 and 1719, 1834, 1842, 1865 and 1893, 1921, 1949, 1959, 1976, 2003 and 2018. Many of these extremes are not only confirmed in other papers, but have also been identified as such in neighboring regions (Doornkamp et al. 1980, Hémon et al. 2003, Poumadère 2005, Koppe & Jendritzky 2014, Cook et al. 2015, Wetter et al. 2014, Glaser et al. 2018, Brazdil et al. 2019b, Erfurt et al. 2019). As expected with drought, the large-scale structure is also evident.

Long-term development

In order to be able to examine the long-term development quantitatively and, above all, to achieve a connection to the modern age, various indices have been derived. The modern SPI1-SPI12 was calculated from the official precipitation data for Germany 1881 - 1996. The strengths and weaknesses of the SPI are now widely discussed in literature (Briffa et al 1994, Cook et al 2015). Its wide distribution and simple calculation as well as the ability to connect to the historical period are

https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

Climate of the Past
Discussions

the reasons why it was used here - and not the more complex scPDSI, as used for example by Cook et al. (2015) or Mikšovský (2019).

The reconstructed SPI for Germany from 1500 onward show high variability on the one hand, and extensive stationarity in the long-term perspective on the other. However, variability is slightly higher in the first 150 years, while it has been reduced over the last 100 years. Also noticeable spikes occur in the SPI time series, which show significant droughts. Medium-term changes characterize, for example, the section 1890 to 1920. Prominet is the increase of 1630 - with the conspicuous sequence of drought years 1630-1635 up to the maximum 1646-1651 followed by a series of wet and humid years. Noteworthy is also the sinking or lack of heavy rainfall since the 1980s. The curves and structures are also very similar to those of Dobrovolny et al. (2015) and Mikšovský et al. (2019), which were reconstructed for the neighboring Czech Lands.

All in all, interesting conclusions about the development of SPIs and droughts in Germany since 1500 can be drawn from the reconstructed time series. To evaluate the quality, the Historical Drought Index (HDI) was correlated with the Modern Drought Index (MDI). The very good correlation of r = 0.75 proves the strength of the relationship.

In order to assess not only the negative hygric events and thus the drought and dryness, but also the positive hygric events, humid and wet events were included. For this purpose, the monthly precipitation indices (PI) of the historical precipitation index (HPI) were used to form the sum of the corresponding number of months, analogous to the SPI. The very good correlations are a conclusive measure of the strength of the statistical context and the quality of the approach. This also applies to the Historical Drought Index (HDI) and the Historical Wet Index (HWI). Both indices have been combined into the Historical Humidity Index (HHI).

The monthly HHI reveals very well the annual structure of individual drought and dry events and clearly shows that not only summery, but especially winter precipitation deficits but also marked positive deviations occurred. It is noticeable that in comparison to the analysis of summer drought comparatively few studies on the winter droughts are available in literature. An exception is, for example, Pfister et al. (2006) with the analysis of hydrological winter droughts of the last 450 years in the Upper Rhine plain. This also applies to the transition seasons.

The medium-term development is presented as a 5-year course. He emphasizes the somewhat stronger eruptions in the first 150 years, especially the great contrasts of the dry period 1630-1635 and the damp phase 1646-1651. This represents the most striking vibration of the last 500 years. The damp phase 1692-96 and the dry period 1740-1744 are also striking. Also, in the period 1750 to 1911 basically more dry months occurred, as in the period after 1911. In the last few decades no striking trends occur - only the most recent extremes accumulate. Seen from this point of view, no comparable structure to the anthropogenic temperature trend can be observed. This also corresponds to the findings of Sheffield et al (2012). Spinoni et al. (2015) confirm this indirectly. According to their analyzes, the drought frequency is increasing in southern Europe, and a reverse trend can be observed in northern Europe. Moreover, they rightly refer to the different methodological approaches.

In order to further develop the internal structure of this time series, the Historical Humidity Index (HHI) 1500-2018 carried out a Fast Fourier Transformation. This results in striking recurrence cycles at 22, 37 and 58 years.

5 Outlook

The elaborations make it clear that there have been significant changes and outstanding individual events concerning dryness and drought events. Of course, the question arises about the reasons and causes. Explanations are given by solar and volcanogenic forcing, which in fact help to understand individual events and phases. At the same time, however, questions of internal variation of the climate system have to be discussed, such as the teleconnections likewise the NAO + and NAO- or connections with the ENSO phenomenon. Nonetheless, today the question of the recent anthropogenic increase in greenhouse gas emissions and a possible increase in drought events and their long-term consequences is of interest. Are there any relevant trends that will show up in the future?

Increasingly, there is also the question of the social impact and long developments. How have climate changes affected human history? Especially in multiproxy approaches such questions are answered (Brazdil et al. 2019, Mikšovský et al. 2019, Büntgen et al. 2010,2011). How the methodical and content-related insights presented here can be integrated into these questions will be the subject of future analyzes.

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Climate of the Past
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Abbreviations, developed and used in the text

PI: Precipitation Index (-3 .. + 3) (Integer)
SPI : Standard Precipitation Index
HPI : Historical Precipitation Index (-15 ... +15):
MDI: Modern Drought Index, DWD drought Index, 5-scale, derived from SPIs
HDI: Historical Drought Index, 5-scale drought index, derived from HPIs
HWI: Historical Wet Index, analogous to HDI for positive hygric indices
HHI: Historical Humidity Index (-5…+5) (HDI Combines & HWI)

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Climate of the Past Discussions
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Figures

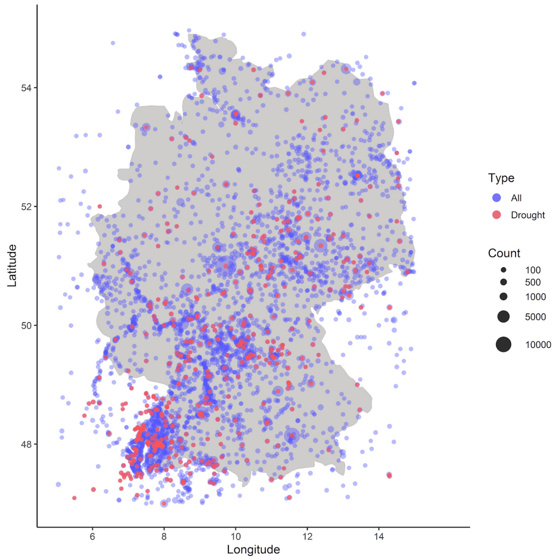
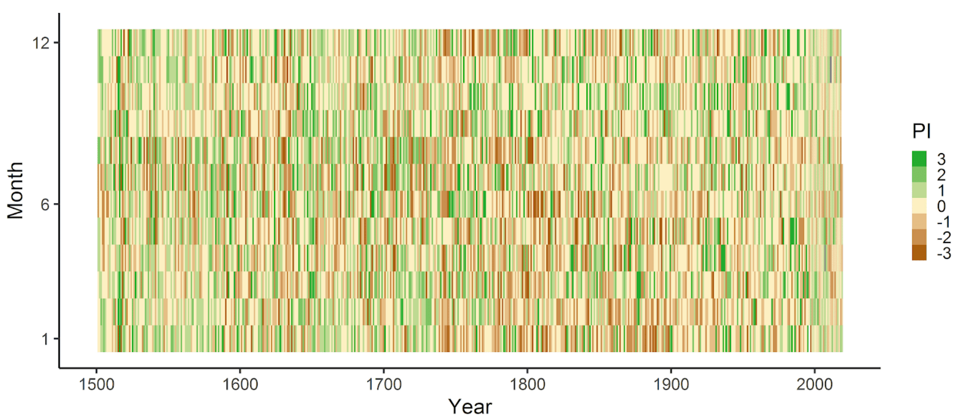


Fig. 1: Spatial distribution of information in tambora.org



460 Fig. 2: Summary of the monthly precipitation index (PI) for Germany from AD 1500-2018

https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

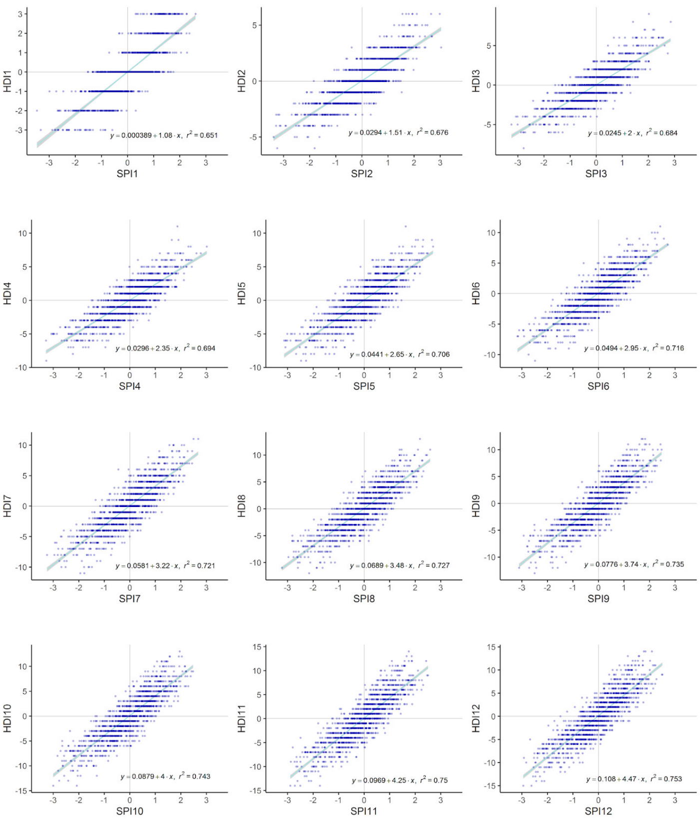
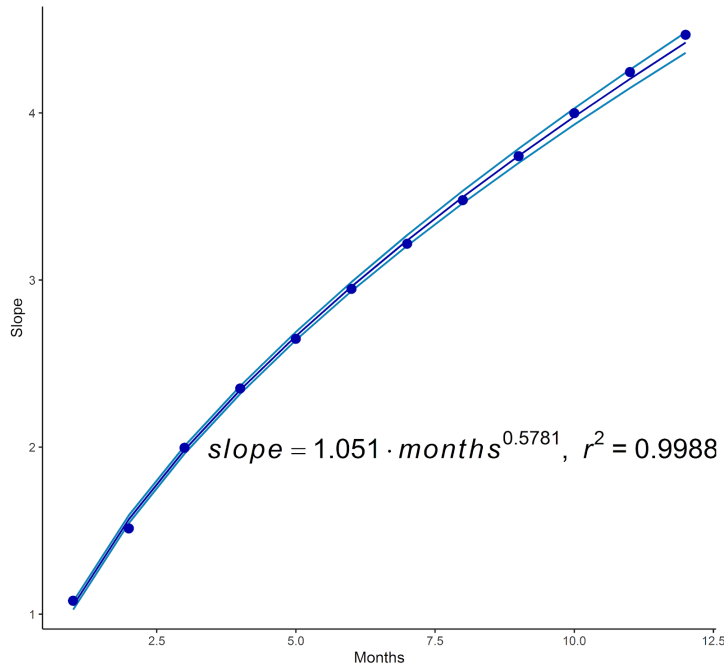


Fig. 3: Strength and shape of the relationship between SPI and HPI 1881-1996

https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

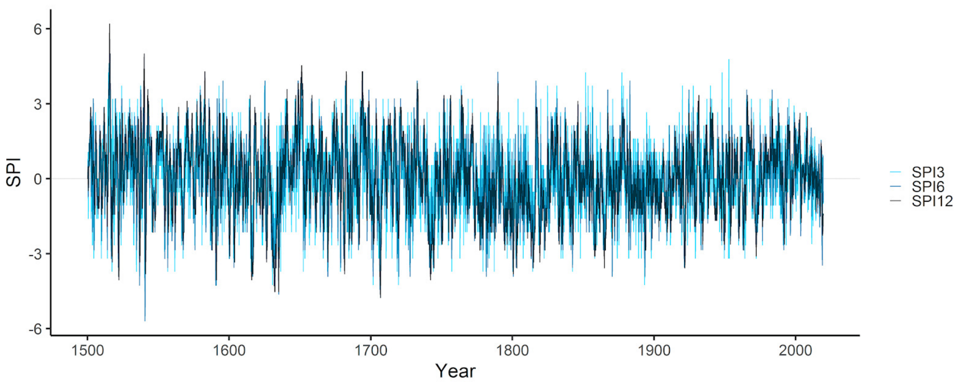
Climate of the Past
Discussions

Months	Slope
1	1.0802
2	1.5127
3	1.9957
4	2.3506
5	2.6475
6	2.9465
7	3.2167
8	3.4780
9	3.7417
10	3.9986
11	4.2452
12	4.4677



$$SPI_i = HPI_i \cdot i^{-\frac{1}{\sqrt{3}}}$$

Fig. 4: Duration and scale factors of the relationship between SPI and HPI



https://doi.org/10.5194/cp-2019-104
Preprint. Discussion started: 12 September 2019

Fig. 5: Historical SPI3, SPI6 and SPI12 for Germany since 1500

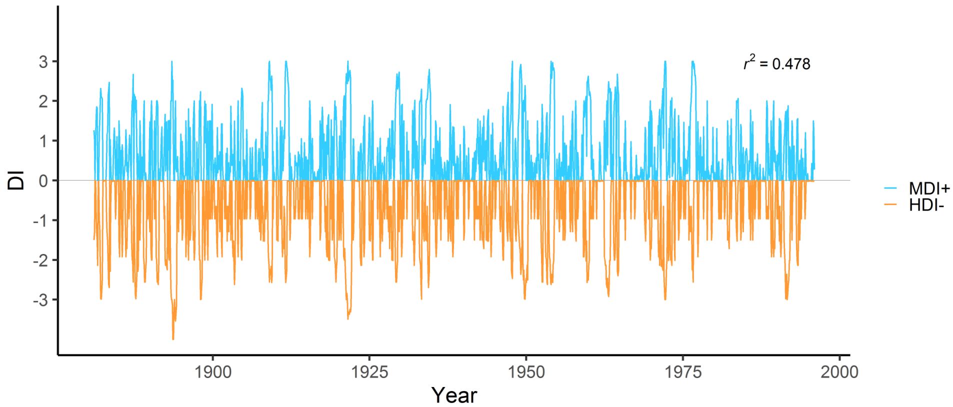


Fig. 6: Historical Drought Index (HDI) vs Modern Drought Index (MDI)

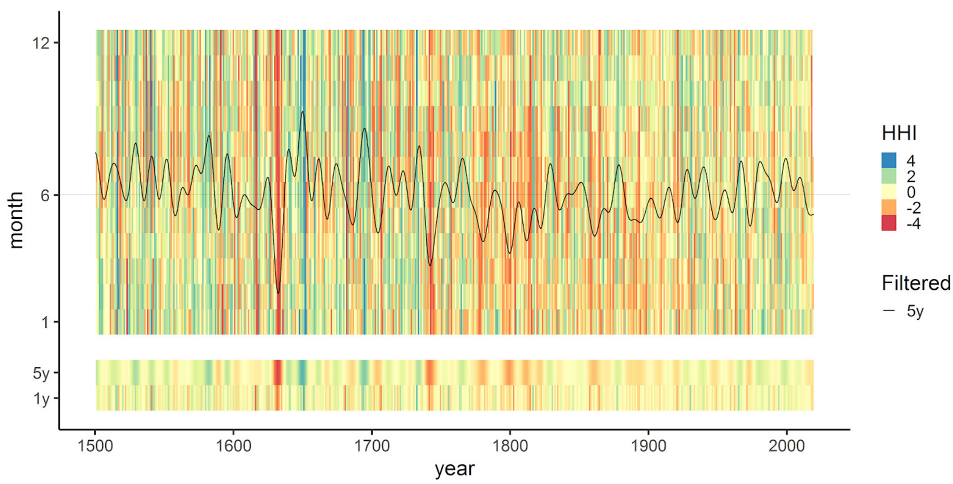


Fig.7: Historical Humidity Index (HHI) for Germany from 1500