Reassessing long-term drought risk and societal impacts in Shenyang, Liaoning province, Northeast China (1200 - 2015)

LingYun Tang[1*], Neil Macdonald[1], Heather Sangster[1], Richard Chiverrell[1] and Rachel Gaulton[2]

[1]Department of Geography, School of Environmental Planning, University of Liverpool, Liverpool, L69, 3BX, U.K.

[2] School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

*Corresponding author E-mail: psltang@liverpool.ac.uk

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Abstract

The occurrence of two severe droughts in Northeastern China since 2000 has raised attention in the risk presented by droughts. This paper presents a historic drought series for Shenyang in the Liaoning province, NE China since 1200 to present, with a reconstructed long precipitation series (1906-2015), augmented with historical documentary accounts. Analysis of the instrumental series using a standardised precipitation index (SPI) and extending it using historical records has produced a combined series spanning over eight centuries. The combined long series was analysed for patterns in drought frequency, severity and typology. Three droughts comparable to those since 2000 occur in the instrumental series during early twentieth century (e.g. 1907, 1916-18 and 1920-21), and coeval archival sources reveal the human impacts of these severe droughts. The archival sources demonstrate how reduced vulnerability resulting from societal and cultural changes in the early twentieth century helped prevent the loss of life experienced during comparable severe droughts at the end of the nineteenth century (1887 and 1891). Incorporating a longer temporal perspective to drought analysis shows that onset is often earlier than is documented explicitly within the archives, and so combined SPI series for a region could provide an early warning of drought development expressed as a water deficit in the previous year. Analysis of archival data provides a rich historical description of impacts and societal responses to severe drought. The archives provide a rich historical description of drought impacts and responses at the personal and community level, whilst also detailing the different roles played by communities, state and international organisations in responding to events.

Keywords: Drought; Reconstruction; Historical; Shenyang; Liaoning, China

1 Introduction

Drought is a world-wide problem, causing more deaths globally than any other natural disaster (Delbiso et al., 2017); with over 485,000 deaths and more than 1.6 billion people adversely affected during the last decade (2010-2019; EM-DAT, 2019). Drought is often a slow developing pervasive environmental disaster that is hard to predict and manage, and a variety of definitions for drought in operational use around the world, there is no universal definition for drought with a variety of definitions used around the world, with many focusing on a deficiency in precipitation over a period of time (Belal et al., 2014; Lloyd-Hughes, 2014; Wilhite, 2000). Droughts are a long-term water deficit, that often develops slowly under natural conditions or through human intervention that causes adverse impacts on activities (e.g. food production) or societal groups (e.g. farmers) (Dai, 2011). Drought often begins following a prolonged period of moisture deficiency (Lanen, 2006; Palmer, 1965) propagating through the hydrological cycle, exhibiting differing spatial and temporal characteristics depending on a variety of factors, for example, antecedent conditions and soil moisture (Heim, 2002; Todd et al., 2013). Wilhite and Glantz (1985) classified droughts into four types: meteorological, hydrological, agricultural, socioeconomic, with Mishra and Singh (2010) recommending the inclusion of a fifth classification ground water drought. Drought has been referred to as a 'creeping phenomenon' (Mishra and Singh, 2010), and its impacts vary from region to region, with drought effects exacerbated by other meteorological elements, such as temperature, wind, and humidity (Brázdil et al., 2008). Palmer (1965, pp.1) notes that "drought means various things to various people, depending on specific interest". Droughts are complex so-called 'natural' hazards – the term 'natural' in natural hazards, although etymologically doubtful, because in a sense all hazards are natural, may be considered as 'natural' as sanctioned by a long-term use in disaster research (Sangster et al., 2018), with droughts causing significant environmental, social and economic impacts (Van Loon et al., 2016). Drought is an international phenomenon with notable drought episodes throughout the twentieth and twenty-first centuries, e.g. 1930s 'Dust Bowl' in the USA (Schubert et al., 2004); 1975-76 in Europe (Parry et al., 2012; Zaidman et al., 2002); China 1994 & 2010-2011 (Zhang et al., 2019) and South Africa 2015-17 accompanied by continued low rainfall (Wolski, 2018). Over the last decade a number of studies have started to explored historical droughts (Brázdil et al., 2009, 2018b) and the impacts experienced over decades to centuries on water resources (Lennard et al., 2015); agriculture (Brázdil et al., 2018a); infrastructure (Harvey-Fishenden et al., 2019); stream and river flows (Zaidman et al., 2002); groundwater (Bloomfield and Marchant, 2013); with recent calls (e.g. Trnka et al., 2018) for more to be done with existing data, particularly in understanding past socio-drought responses and changes in vulnerability. Considerable work has been undertaken in recent decades in developing robust and long flood and drought chronologies using combinations of archival (Brázdil et al., 2018b; Yan et al., 2014; Zheng et al., 2006) and instrumental (Brázdil et al., 2009) sources from around the globe, although much work to date has focused on Europe (Wilhelm et al., 2018). The development of new online digitised sources has facilitated greater historical analysis (Black and Law, 2004; Wang et al., 2018) with greater recognition from regulatory authorities of the value of historical information (Kjeldsen et al., 2014).

China is one of the most natural disaster-prone countries in the world (Dai, 2011; He et al., 2011; Loorbach et al., 2011), and droughts are a recurrent feature of the Chinese climate (He et al., 2011). Drought can be considered as the most disastrous natural hazard within China, with over 465,000 deaths and more than 3.1 billion adversely affected from 1970-present and 12 million deaths since 1900 (EMDAT, 2019). Historically notable droughts in 1876-1878, 1928-1930 and 1958-62 resulted in widespread loss of life, poor harvest, leading to serious social consequences of famine, robbery, unrest, and political instability (De Châtel, 2014; Janku, 2018; Teklu et al., 1992; Yang et al., 2012). Between BC 206 and AD 1948, 1056 severe droughts are recorded in Chinese history, though not spatially coherent (Zhang, 2004, 2013); in the period 1949-2000, Zhang et al. (2008b) identify 10 years of 'heavy'(severe) agricultural drought, and 4 years of 'extreme' agricultural drought. Precipitation recording in China has developed through time, with some of the most advanced recorded globally during the Qing Dynasty (CE 1644-1912), with both rainfall and snow depth recorded from 1736 to 1911 (Ge et al., 2005). The installation of better equipment through the 1920s and 1950s saw many stations upgraded, with meteorological stations often retained; however, the availability of metadata on early recorders is more limited. Past droughts have had a far-reaching impact on society in China; a clear understanding current and future drought risk is therefore critical. With population growth, economic development, urbanisation and climatic change, drought is a global challenge, but drought poses a serious threat to food security, environmental ecology, urban and rural water supply in China (Bohle et al., 1994; Homer-Dixon, 1994).

This paper examines the history of drought in the Shenyang region of Northeast China, the spatial and temporal variability in droughts, the characteristics of droughts, and mechanisms responsible and impacts on society. Our objectives are:

i. To develop and analyse the record of droughts and the documentary evidence for associated impacts (1200 AD - present), using a variety of sources including the compendium of Chinese droughts produced by Zhang (2004, 2013);

ii. Identify and analyse contemporary droughts using the instrumented daily precipitation series at Shenyang Meteorological Observatory (Station 54342: 1961-2015), and augment this series with the longer monthly precipitation data for Shenyang (1906-1988);

iii. Generate a Standardised Precipitation Index (SPI-1, -6 and -12) for the augmented precipitation series spanning the period 1906-2015; construct one of the longest drought series (1200 - present) combining the augmented instrumental series (ii) with historical data (i), and then classify the different types of drought and event severity; and,

iv. Analyse the patterns in drought frequency, severity and type for Shenyang, examining the documented impacts and responses to drought to better understand how societal vulnerability has changed through time.

2 Study Area

Shenyang (41.8°N 123.4°E) is the capital city of Liaoning Province in Northeast China (Figure 1), with a temperate continental monsoon climate, with temperature ranging from -17ºC (January) to 29ºC (July), decreasing from southwest to northeast (plain to mountain) (Chen et al., 2016); whilst average annual precipitation (500-1000 mm a^{-1}) increases from west to east (Zhang et al., 2013). The Shenyang municipality is home to approximately 8 million people in 2016. The region has witnessed reductions (at 78% of stations) in annual precipitation over the period 1961-2008 (Liang et al., 2011). The Liaoning province is a primary grain producing region in China; as such droughts and associated impacts on regional agricultural production are of national importance, with previous studies detecting recent warming and reductions in precipitation (Chen et al., 2016).

3 Data and Methods

3.1 Data sources

This study uses a variety of source materials including historical and instrumental datasets detailed below.

3.1.1 Documentary data

The 'A compendium of Chinese Meteorological Records of the Last 3,000 Years' produced by Zhang (2004) and updated in 2013, summarises 7835 historical sources from the earliest existent materials in the Chinese language, the ‘Oracle Bones Collection’ (c.1600 BC) through to more recent sources which describe meteorological incidences in China. The ‘Oracle Bones’ have a long history of being studied for meteorological information, with early studies undertaken by Wittfogel (1940). There are also a small number of private diaries and court memorial files of the Qing Dynasty, though the ‘History of Drought Archives in the Qing Dynasty’ (Tan, 2012) provides a summary of the collection spanning from 1689 to 1911, with more than one million pieces present in the Qing Dynasty palace archive. The China Meteorological Disasters Ceremony (Liaoning volume) from Wen et al. (2005) provides detailed accounts of drought alongside records of other disasters which may have been caused by drought, such as famine and plague; a full list of source materials can be found in Table 1. Over recent decades considerable effort has been placed into collating the archival materials present across China detailing natural hazards, this wealth of information provides valuable opportunities for further exploration; however, such volume limits the capacity for cross checking and validation, with many sources not easily accessible. This has raised questions of reliability and transparency, but as Bradley (2006) notes, the compendium produced by Zhang (2004) clearly illustrates critical analysis, with careful checking for consistency and discrepancies identified. Recent developments include a move to digitise these databases, ensuring and maintaining high levels of archival practice, with the development of the REACHES (Reconstructed East Asian Climate Historical Encoded Series) climate database (Wang et al., 2018).

In addition to the meteorological sources identified, information from sources detailing agricultural activity provide valuable auxiliary reference materials, including the following items: Shenyang local records (Meng, 1989; Shenyang Municipal People’s Government Local Records Office (1994-2011), 2011); The year of flood and drought in Shenyang from 1276 to 1985 (Shenyang Municipal People’s Government Local Records Office, 1998). The following datasets have been acquired from the Office of State Flood Control and Drought Relief (1999); Farmland affected area from 1949 to 1990 in Liaoning Province Statistics on Drought Area of Heavy Drought in Liaoning Province; Drought rating assessment in various regions of Liaoning Province from 1949 to 1990; Drought Statistics in the Province from 1470 to 1949; Comparison of Precipitation in Liaoning Province from 1949 to 1964 and from 1965 to 1990; Comparison of grain yield per plant, drought frequency and drought reduction in various regions of Liaoning Province; hydrological station data for Liaoning Province; Regular frequency of continuous drought in dry season in Liaoning Province. Local newspapers have also been accessed to corroborate records of droughts e.g. the Shengjing Times (Shenyang was previously called Shengjing – see Table S1).

3.1.2 Instrumental data

Instrumental climate data are taken from two datasets, the first is long-term meteorological data, including monthly precipitation (05/1905 to 12/1988) from the Research Data Archives Computational & Information Systems Lab (NCAR, 1996), no records present for 1944-1946. The precipitation records for Shenyang have also been viewed and photographed in the Chinese Meteorological Archives in Beijing. The second precipitation series was retrieved from the National Disaster Reduction Centre of China (NDRCC), which provides daily data for air pressure (parameter code: V10004), daily average temperature (V12001), daily highest temperature (V12052), daily lowest temperature (V12053), precipitation (V13201), average wind speed (V11002), sunshine hours (V14032), for the period 01/01/1961 to 31/05/2016. This study uses the precipitation data (V13201), however, subsequent drought analysis could use the additional data for more complex drought modelling. Analysis of these datasets permits varying temporal analysis of the precipitation, with a long overlap period that can be used to compare the association of these two data sets.

Previous studies have illustrated a strong relationship between droughts and ENSO anomalies (Li et al., 2019; Zhang et al., 2018b) for differing regions of China. However, many of these studies use relatively short series (1960-2015). The extended precipitation series (CE 1906-2015) presented here provides a valuable opportunity to explore this relationship over a longer timescale. The Niño 3.4 sea surface temperature index, defined as the area-averaged SST anomalies over (5N–5S, 170–120W), compiled from PSD using the HadISST1 dataset for the period 1870-2015 by Rayner et al., (2003) is used in this study.

3.2 Data processing

3.2.1 Documentary data

The compendium provided by Zhang (2004, 2013) provides the framework for the early record (pre-1911); however, great care was undertaken in assessing the historical record through verification of original accounts.

In the process of analysing documentary sources for Shenyang, it is necessary to pay particular attention to historical changes to the name of Shenyang and the boarders of the provinces (see

Table S1). For example, in the book “Zhong Guo Dong Bei Yu Dong Bei Ya Gu Dai Jiao Tong Shi” (Wang and Pu, 2016), it is noted that during the Han Dynastry, ‘Liao Dong Jun’ was used for the Shenyang area, whereas during the Dong Han Dynasty, the southern part of Shenyang continued to belong to Liao Dong Jun, and the northern part belonged to Xuan Tu Jun (Zhao, 2006). In addition, the Gao Xian region is the recent Sujiatun area in Shenyang (Wang and Pu, 2016); Yan (2012) detailed the historical changes in the Shenyang (Table S1).

Historical records for all drought years are included where records exist, but historical records for the following situations are excluded:

i. Information unclear - the disasters cause or event location is unclear. For example, in 1549, the drought and locust disaster occurred in Xingcheng County of Liaoning Province ("Ming Shi Zong Shi Lu", Vol. 353). In 1549 Xingcheng belonged to Liaoxi; however, Shenyang belonged to Liaodong, therefore, this record is not in the target region and is excluded.
ii. A record is excluded if it does not clearly state drought, or that a drought was the cause. Although there are many types of event that are associated/related to droughts, such as locusts, epidemic disease or famine, where historical records do not directly state drought or attribute the cause to drought they are excluded. For example, in October 1551, the Liaodong area did not collect grain tax because of disasters ("Ming Shizong Record", Vol. 3, 7:8). The record does not specifically state that a drought occurred though this is a common response to a drought.

3.2.2 Instrumental data

Data quality assessment and management of both long (NCAR) and shorter (NDRCC) series was required to ensure homogenisation and data suitability (see section 3.1.2). Total precipitation includes both liquid and equivalent frozen precipitation. All meteorological variables are recorded as one-tenth of their specific units (mm), but are converted to mm throughout. For both instrumental series, care and attention was taken with the original data series quality, with the data descriptors recorded in Table 2. At Shenyang meteorological station, missing data occurred eight times (representing 0.826% of the record), and rainfall was marked three times with ‘R’, reflecting monthly totals identical to the previous month, raising concerns as to the validity of the data (01-02/1906, 12/1908-01/1909 and 12/1968-01/1969). There is a reduction of available meteorological data during the years 1943-46 following the Second World War across much of eastern China, as such no suitable local sites could be identified to infill this series; for other missing monthly data, the monthly averages are included where single months are missing, as often other local stations also have missing data. For the shorter instrumental daily precipitation series (NDRCC), data descriptors are included in Table 2, including percentage of record impacted. The precipitation record for Shenyang has four station relocations/instrument renewals during its monitoring record (October 1970, October 1976, January 1989 and June 2006). An analysis of the homogeneity of the record was undertaken using the approach presented by Li et al. (2014), when assessing temperature changes in Shenyang. A correlation analysis of Shenyang with the nearby Benxi precipitation station record (~41 km southeast of Shenyang) demonstrates a stable difference (prediction ration) between the two series for all periods and an R^2 throughout of >0.88 (Table S2). In the absence of any evident changes within the precipitation record resulting from localised station relocation/instrument renewal we consider the precipitation data at Shenyang to be homogeneous and reliable.

Analysis of the two series coeval years of record (1961-1988) was undertaken, a Q-Q plot was undertaken to verify that both data sources are normally distributed (Figure 2a). Figure 2b shows a good linear distribution (p-value of 0.028); however, differences between the series exist. During the period 1961-1988, the average difference between the two datasets is 12.72 mm and the maximum is 313.2, which occurred in October 1974; further examination reveals that all the differences occurring in the period 1961-1979, with the two datasets producing identical values for all months from 1980 onwards, this replicability in the later records provides confidence in extending the NCAR dataset through to the present (2015). Analysis of the dispersion and outliers for each month was also undertaken (Figure 2c), the months with greatest discrepancy are March and April, possibly reflecting challenges of recording snow/ice fall. Comparison of the monthly and seasonal precipitation patterns presented in Figure 3 for Shenyang for the period 1906-2015 using the new augmented series illustrate that some of the anomalous values from NDRCC data from the period 1961-1979 appear unrealistic, e.g. 04/1964, 285.9 mm, with an average normally of c. 50 mm. An analysis of the variability in the precipitation is presented (Figure 4), with the lowest precipitation (the driest, 1913: 341.1 mm a^{-1}) and highest (wettest) years noted (1923: 1064.9 mm a^{-1}; Figure 4a); a seasonal analysis and long term trend are also presented (Figure 4b-e) with a 30-year Savitzky-Golay filter (Savitzky and Golay, 1964).

3.3 Drought Identification

Using the combined instrumental and archival source materials, a record of droughts will be reconstructed for Shenyang, the droughts will be explored and examined from a number of perspectives including: type of drought (classification), intensity/magnitude, frequency and trends; together these characterise the drought structure.

3.3.1 Standardized Precipitation Index (SPI)

A number of drought indices have been developed Heim (2002). Meteorological drought indicators can be divided into two categories focused on either the physical mechanisms of drought or the statistical distribution of meteorological elements; the SPI belongs to the latter group and is widely used (Lennard et al., 2015; Mckee et al., 1993). As the long precipitation series includes only monthly data, the Standardised Precipitation Index (SPI) is used, this index has a number of advantages when used over long timescales compared to other potential drought indices. The SPI developed by Mckee et al., (1993), is a widely applied meteorological drought index that quantifies precipitation deficits or excess across different climates at multiple timescales, typically of 1–24 months, however the simplicity of the SPI (precipitation as the only input) causes some limitations too, e.g. no consideration of evaporative demand (Vicente-Serrano et al., 2014). SPI values are dimensionless units, with negative values indicating drier than normal conditions and positive values wetter than normal conditions. Drought onset is generally assumed to occur at SPI values exceeding ≤1, however the National Standards of the People’s Republic of China (2017) classification uses ≤0.50 as indicative of drought onset, with drought termination identified as when SPI returns to ≥0 (Table 3a); within this study we apply the classification as defined for China. SPI can be used to characterise drought duration, severity and timing of onset and termination (together known as the drought structure e.g. Noone et al., (2017)), based on the classifications identified in Table 3a; the SPI classification recommended in China (National Standards of the People’s Republic of China, 2017) differs slightly from that of the WMO (2012; Table 3 (a and c), though others have also proposed regionally specific SPI versions based on Mckee et al. (1993) e.g. Moreira et al. (2008) for Portugal. Drought duration is determined by the number of months between drought onset (SPI ≤0.49) and termination (SPI ≥0), drought severity is categorised using the SPI classification system with peak severity the minimum SPI value recorded during the drought. Within this study SPI will be examined at three temporal scales SPI-1 (1 month), SPI-6 (6 months), and SPI-12 (12 months) (Figure 5a-c). The SPI was determined by fitting a probability density function to selected accumulation periods using L-moments to estimate parameters. A gamma probability density distribution was found to be the most appropriate fit, using a Kolmogorov-Smirnov (K-S) test to compare empirical and theoretical fit, calculating the cumulative probability. This was then converted into the standard normal distribution, with transformation of the cumulative probability of the fitted distribution to standard normal distribution to define the SPI value (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano et al., 2010). Other univariate distributions have been recommended where a gamma distribution is not appropriate (Barker et al., 2016; Stagge et al., 2015).

3.3.2 Documentary analysis

Documentary data provides additional information beyond that offered by instrumental series, providing valuable information detailing both societal impacts and responses to past events (Pfister, 2010). At Shenyang, the first recorded drought occurs in 347 AD, but only three events are recorded during the period 347-1200, therefore the records analysed within this paper start post 1200, as the frequency of records increases. Previous studies (e.g. Brázdil et al., 2009; Hanel et al., 2018; Todd et al., 2013) using historical archival sources have examined qualitative records and used a variety of different indices or grades of drought. The use of ordinal index systems for the classification of descriptive accounts in historical climatology is common, with a range of classes used e.g. Nash et al., (2016) used a +2 to -2 classification in examining wet/dry phases in Natal and Zululand in Southern Africa. In augmenting the instrumental with the historical series, clear benefits can be achieved if the descriptive classification is comparable to the SPI drought classification applied in China (Table 3a). Therefore, five drought classes are used in considering the historical descriptions, allowing alignment between the two data forms, typical types of descriptor for each of the five classes are presented in Table 4.

Analysing the historical records unearthed different forms of drought which broadly reflect the five drought classes identified by Mishra and Singh (2010); meteorological, hydrological and agricultural are comparable, the difference being few accounts detail groundwater droughts (incorporated into hydrology within this study), with the socio-economic class being split into economic (impacts of clear cost) and social impact (impacts on people e.g. health). In splitting the socio-economic class into economic and social impact the wealth of materials present, in the historical record examining these aspects can be examined in greater depth. Each of the different classes of drought increases in impact severity (Table 4) in documenting each of these an assessment of the interrelationship between different types of impact can be made, for example, the point at which food relief may be initiated, or tax payments suspended (typically class 2/3), others such as praying for rain/snow are associated with high classes (4/5), reflecting personal, community and governmental responses (e.g. government control of food prices).

Annual drought values for the instrumental period (1906-2015) are represented by the minimum SPI-12 value within each calendar year; within the documentary accounts the most severe class of drought is used to determine the classification. We opted to use the SPI-12 in preference to SPI-6 (or shorter timescales), as precipitation in Shenyang has such a strong seasonal skew toward the summer months, use of SPI-12 also permits a stronger analysis of interannual drought, a key feature in this paper over the long-period analysed.

3.3.3 Drought trend and frequency analysis

The combined long-term drought series for Shenyang (1200-2015) permits an analysis of the long-term drought trends and patterns. Clearly over such a long timescale a number of socio-political and cultural changes will have occurred (Bavel et al., 2019), which may influence the extent or severity of a particular drought and the capacity a population has to respond to a drought of any given magnitude or severity (Keenan and Krannich, 2010; Kreibich et al., 2019; Mechler and Bouwer, 2015). Human interventions may mitigate and/or exacerbate the impacts of drought downstream through hydrological system management and engineering (He et al., 2017). The socio-political and cultural circumstances during each recorded drought will represent an important underpinning in considering long-term drought trends and variability and will be considered individually in each instance (see discussion by Brázdil et al., 2020).

An analysis of the different types of drought will be undertaken, assessing long term variability, severity and frequency, including examination of where droughts have been documented during the instrumental period. The severity of droughts will be considered using the different classes of drought, examining whether any notable differences in drought type emerge, which may help determine underlying changes in vulnerability through time. The reliability of the historical account classification process was assessed for the period 1906-2015 by statistical analysis (Spearman - ordinal drought class) of the assigned drought class to annual minimum SPI.

The principal challenge identified within this study is in attempting to assess droughts defined between those characterised by the historical analysis which is subjective and that defined by the indices (SPI), which assumes a distribution with predefined probabilities attributed to each class (Guttman, 1998). Whilst an advantage in drought risk analysis, this makes it challenging for comparison to a subjective classification.

4 Results and Discussion

4.1 Temporal analysis of instrumental time series

The augmented precipitation series illustrates the range of precipitation experienced at Shenyang over the last 110 years, with a maximum annual rainfall of 1064.9mm (1923) and a minimum of 341mm (1913). The mean of 704 mm is slightly higher than the median value (red dashed line; Figure 4a). Of the 28 years annual rainfall below the quartile, 10 occur prior to 1960 and 18 after. Precipitation at Shenyang is concentrated in the summer months, with little winter precipitation (Figure 3), typical of a continental climate. Documentary accounts often discuss spring droughts in Shenyang, which hinders the development of crops at the start of the growing season (Wang et al., 2019).

Seasonal analysis of precipitation (1906-2015: Figure 4b & 4e) illustrates that precipitation in winter and spring gradually increases with time, with a slight reduction of summer and autumn precipitation, but are statistically insignificant (at 0.05 level; Figure 4c and d). The most severe spring drought occurred in 2001, with only 33.7mm spring precipitation, this is supported with widespread media coverage of the drought in Shenyang and more widely in Liaoning. The worst summer drought occurred in 2014 (170.6mm), with precipitation less than fifty percent of the norm, presenting the worst summer drought since 1961; in response the Liaoning provincial government instigated a level III drought emergency response, this included additional funding from central government (150 million yuan) and provincial departments (70 million yuan) (Wang, 2014), with drought relief teams created to support community water infrastructure projects (Sun, 2015).

The SPI generated from the long precipitation series is analysed at SPI-1, -6 and -12, with SPI-1 suited to short-term (monthly) analysis, with SPI-6 appropriate for seasonal drought analysis and SPI-12 for annual to multi-annular droughts. SPI-6, with scores of ≤-2 (severe droughts) occur 14 times during the 110-year record (Figure 5b and c). There are six severe drought years before (1907, 1913, 1914, 1917, 1920, 1926) and eight (1961, 1963, 1965, 1989, 1997, 2000, 2014, 2015) after 1960, with several of these constituting multi-annular droughts. There are seven droughts that exceed ≤-2 in the SPI-12 series (Figure 5c)**.**

4.2 Drought classification and trends

The reconstruction of historical droughts in Shenyang is divided into two parts. The first obtains drought class information from the SPI for the period 1906-2015 from an augmented instrumental series. The second uses historical documents and is defined based on specific classification criteria shown in Table 2 producing a long drought reconstruction from 1200 AD to 2015, with documentary (coloured) and instrumental data (black) for Shenyang (Figure 6b). Analysis of the period 1906-2015 demonstrates a non-statistically significant correlation exists in the relationship between annual minimum SPI-12 and documentary drought class for any given year, of the 107 years of record, 42 record both an SPI and descriptive account of drought. The relative absence of class 1 events in the documentary record suggests that no account is often made during ‘normal’ conditions, with absence of record often likely reflecting no drought, therefore the analysis was repeated, years with no description were attributed to class 1, as a result a statistically significant relationship is identified (Spearman, $p<0.05$).

There are few early records from the thirteenth and fourteenth centuries, however there is a small peak in Figure 6c indicating that the region experienced increased droughts, and as Li (2019, 168) reflects the period was one of “non-stop calamities” elsewhere in China. The low number of accounts during this period for the Shenyang region may reflect limited recording rather than non-occurrence. There is a clustering of events during the fifteenth and sixteenth centuries, these events are evidenced across multiple drought types, with several being Class 3, including droughts in 1434 and 1450 respectively and the Class 4 drought of 1501, which are described as:

“夏，辽东不雨，亢旱为灾，农田虽种，无收获者多” [Summer, Liaodong no rain, drought disaster. Although farmland sowed, most people do not have harvest grain.]

(Ming Shi Lu, Ming Xuan Zong Zhang Emperor Record, Vol. 112),

“夏五月，减免沈阳等卫夏税十分之七，秋粮子粒十分之四” [Summer May, reduction and exemption of Shenyang and other regions summer taxes for seven-tenths, autumn grain crops four-tenths.]

(Ming Shi Lu, Da Ming Ying Zong Rui Emperor Record, Vol. 192)

and,

“春至秋，辽东不雨，河沟尽涸。” [From spring to autumn, Liaodong no rain, the river and ditch dry up.]

(Ming Shi, Zhi Di Liu, Wu Hang San. No. 10)

This drought period is coeval with a previously identified reduced monsoon phase in Central China (Zhang et al., 2008a) and the Spörer period (1460-1550) of reduced solar activity, which coincides with a cold phase in China as noted by (Zhang et al., 2018a). This represents a notable drought rich phase, with multiple types of droughts recorded (Figure 6b-c), it also coincides with a megadrought identified across much of Europe (Cook et al., 2015) and parts of north Amercia (Cook et al., 2014), suggesting that this drought may have extended across more of the northern hemisphere than previous identified.

A relative quiescent phase is then noted between 1600-1750, with few droughts recorded (Figure 6b). A number of droughts occurring in the period 1750-1880 AD are documented; however, the frequency and severity of droughts increases thereafter (Figure 6c). The first drought year with an assessment of class 5 occurs in March 1883, with the Shenyang chronicles referring to drought, a cholera epidemic, and more than 20,000 deaths in a week (Shenyang Municipal People's Government Local Records Editing Office, 1989). This was followed by a second event in 1891, with documentary sources detailing famine and over 20,000 estimated deaths (Wen et al., 2005). Table 5 summarizes the frequency of droughts at Shenyang in each century, with a small peak in Shenyang drought frequency from 1501-1600, drought frequency then decreased until the nineteenth century (Figure 6c).

The frequency of class 5 drought events indicates an increase during the twentieth century, but this is not evenly distributed with most (66%) of those events occurring in the period 1906-1921 (1907, 1913-14, 1916-18 and 1920-21), with only three severe <-2 (SPI-12) droughts events after 1921 in Shenyang in 1968-9, 1999-2002 and 2014-15 (Figure 6a). The documentary accounts in the period 1906-2015 provide valuable corroborative evidence when compared to the annual minimum SPI-12 data, with most documentary accounts recorded as class 2 and 3, with few events classified as either 1, 4 or 5, although the presence and magnitude of the early droughts in the period 1906-21 are corroborated with documentary accounts classed as 4 and 5, with documentary evidence in 2002 also supporting a class 4 drought.

The types of drought recorded within the records are indicated in Figure 6b, these illustrate that the majority of records document meteorological drought conditions, followed by economic impacts. The drought severity in the descriptive accounts' places most of documented droughts in class 2 and 3 (Figure 6b). The absence of deaths being documented restricts the number of class 5 socio-drought, although the drought of 1920-21 is documented as a class 5 hydrological drought, the only documentary class 5 event in the twentieth century. It may be that such information was not published, and/or that the droughts within the Liaoning province did not lead to such impacts, as few events prior to the late nineteenth century approach class 5. In focussing on the city of Shenyang, there is also a risk that the impacts differed within the city to those experienced in rural communities within the province, thereby reducing the number of agricultural droughts documented. Future works should therefore focus at the provincial scale to incorporate a wider diversity of impact.

4.3 Societal vulnerability to droughts

The transformation of responses in Shenyang from *pre-industrial* (*folk*), to *industrial* (*technological*) and subsequently *post-industrial* (Chester et al., 2012; White, 1974) during the period of study presents challenges in assessing and comparing impacts. Recent droughts of comparable meteorological severity, e.g. 2014 (SPI-12: -2.8) to those of the early twentieth century, namely 1907 (-2.6), 1917 (-2.8) or 1921 (-2.5) illustrate how the responses and resulting impacts potentially differed. In analysing these events the consequences of the droughts differed considerably, whilst these events do not record deaths among the population in Shenyang and/or Liaoning province they are severe, with the 1920-21 drought described as "Spring drought for several months, well and river dry up, land dry up, no harvest at all, winter disaster victims everywhere, people live in hunger and cold move out from the mountain village, village empty" [class 4 socio-drought but class 5-hydrological] (Office of State Flood Control and Drought Relief, 1999, p.388), across China an estimated 500,000 people died (Edwards, 1922). Analysis of the international media at the time reporting on the event is shaped by the socio-political circumstances, with The Times (London) recording 3 million as being displaced (9 Nov. 1920 p.11); however, as Fuller (2011) importantly notes this is often viewed from an international perspective, with local relief providers often failing to receive recognition. The responses to the drought varied, but included those expected within an *industrial* framework, with both national and international relief occurring, but also local support complimenting *pre-industrial* responses, with the Shengjing Times (1920) reporting on the 1st July that "Chief Zhang set up an alter begging for rain" (6080, p.4). However, as Li (2007) notes in north China, population increases without apparent agricultural intensification or expansion during the late nineteenth century may have contributed to an increased susceptibility to drought associate harvest fluctuations. In comparison during the 2014 drought which resulted in a Level III emergency response, itself a notable difference from 1920 as a plan was in place, a number of responses were deployed to mitigate the impacts of the drought, these included: the provision of central and provincial relief funds (see section 4.1); water transfer of 400,000,000 m^3 from the Hun River, securing domestic and agricultural provisions (Sun, 2015); and the provision of relief service teams to support local infrastructure improvements e.g. drilling new wells and supply or water to over 32,000 people suffering shortages (Wang, 2014). The impacts of the drought were widely reported in the media, with notably commentary focused on the impacts to water supplies and food production: "Food production in Liaoning… estimated to decline by 5 billion kg this year" (China Daily, 2014). Whilst both events 1920-21 and 2014 were severe droughts, the relief planning and coordinated effort coupled with improved infrastructure and a more stable socio-political environment facilitated a more efficient response.

4.4 Contemporary droughts and generating mechanisms

Analysis of contemporary droughts through coupled documentary sources and SPI provide valuable insights into the importance of drought severity and duration on associated impacts. The 'severe drought' as defined by the SPI of 1968 (SPI-12: -2.13, duration 26 months) appears to have a relatively limited impact in Liaoning province, with few accounts recording particularly notable impacts beyond reduced agricultural output, whereas, interestingly, the drought of 08/1979-07/1983, whilst not a severe from the perspective of the SPI (-1.8), but of longer duration (47 months) receives greater coverage within the documentary accounts, possibly reflecting the duration and cumulative impact on agriculture. This is further supported as the drought of 07/1999-04/2002 (SPI -2.3, duration 34 months) receives similar levels of documentary coverage to that of 1979-83 and 07/2014-15 (SPI -2.8; 18 months, but extends beyond the end of the record) also receives more detailed descriptions.

Documentary accounts often identify that droughts begin in the spring months, but the SPI results suggest that deficits often appear in the previous late summer (e.g. 1968-1969 and 1999-2002 droughts), suggesting that the impacts of dry previous summer and/or autumn are not particularly noted within the documentary accounts, and it is only when the impacts are felt that the consequences are noted. Analysis of the seasonal precipitation to the seasonal ENSO3.4 series shows no significant correlations, but annual minimum SPI has a significant (95% level) correlation with ENSO3.4 Summer (p= 0.0168) and Autumn (p= 0.0228) for the period 1906-2015. This may be explained by the accumulated SPI-12, which reflects a long term deficit, resulting in the severest elements of the drought materialising in summer/autumn, therefore the correlation with summer and autumn ENSO3.4 is a reflection of a longer lagged drought accumulation process.

5 Summary

Our analysis capitalises on the long instrumental and documentary accounts available for Shenyang and the Liaoning province in NE China, by constructing a homogenised precipitation (SPI) series for 1906-2015, and a long documentary drought series 1200-2015. Previously documented notable droughts in the early twentieth century (1907, 1916-18, 1920-21) are compared to the droughts of the last two decades (1999-2002 and 2014-15), illustrating that these have comparable drought structures, with duration potentially being more important than the specific drought severity when considering the societal impacts. It illustrates that recent severe droughts (1999-2002 and 2014-15), whilst notable, are not unusual within the region, with several similar magnitude events in the early twentieth century. Societally the most impactful droughts in the region occurred in the late nineteenth century (1883 and 1891), whilst appearing of comparable structure to those that occurred later (e.g. 1920-21 and 2014-15), social and cultural circumstances resulted in greater social disruption and vulnerability. Reduced vulnerability to severe droughts is evident from the early twentieth century as greater drought mitigation planning and central support are available (see responses to 1920-21 and 2014-15 drought, section 4.3). The relative low number (one) of documentary accounts recording class 1 events reflects preferential recording of more notable events (class 2-5), and remains challenging in any documentary analysis reconstructing climate, as mundane conditions are often overlooked and therefore unrecorded. Further analysis is needed of the drought rich phase identified around the start of the sixteenth century (Figure 6c), whilst the impacts are not considered as great as those of the late nineteenth century, they are frequent and notable.

The calibration and augmentation of historical records with the instrumental series using the SPI presents challenges. Whilst there appears to be good agreement of drought classes 2-4, the probabilistic underpinning of the SPI inevitably ensures some high magnitude drought events are present (class 5), however this is not necessarily reflected within the documentary sources for all drought types. The impact of the probabilistic SPI structure potentially over recording class 5 events is mitigated to some degree with the application of a long precipitation series, where the potential of such events to be recorded increases. Analysis of the documentary droughts in the late nineteenth century suggests that the duration is comparable to those of the early twentieth century, with similar generating mechanisms, a dry winter and/or spring followed by a hard drought in late summer, often spanning multiple years, however the impacts on the communities differ. The vulnerability of populations to drought changes notably over the study period, with the qualitative records and analysis capturing these changes. Therefore, where near the start of the recording period loss of life would have been more common, the same magnitude drought now does not result in loss of human life as resilience has increased. Our identification of a 'build-up' period prior the severest droughts (and their associated impacts) is notable, which is further reinforced by the significant relationship to summer and autumn ENSO3.4 and should be incorporated into future drought management plans, enabling the effective preparation of drought plans.

Data availability

The precipitation series are available from Table 1. Carbon Dioxide Information Analysis Center/Environmental Sciences Division/Oak Ridge National Laboratory/U. S. Department of Energy (1996): Two Long-Term Instrumental Climatic Data Bases of the People's Republic of China. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. http://rda.ucar.edu/datasets/ds578.5/. Accessed† 10-12-2018. The second series (1961-2015) daily precipitation was supplied by National Disaster Reduction Centre of China, data use and access permitted through their involvement in project (NE/P015484/1).

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Competing Interests

None

Author Contribution

LT undertook research, writing and analysis; NM, RC and HS supported LT in writing, data analysis and research approaches; and RG, supported through comments and grant PI for NERC-GCRF grant (NE/P015484/1). NM, HS and RC LT PhD supervisors at UoL.

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Table 1: Historical source materials used in the drought reconstruction for Shenyang

Years	Location	Notes in material	Author/ Year	Source
23rd century BC - 1911 AD	China	The collection of various weather, climate, and atmospheric physical phenomena in history, including flood, drought, rain and snow, cold and warm weather, freezing, frost and other records. There are 7835 kinds of historical materials used in the data set, including local chronicles, historical biography, notes, inscriptions, private diaries, and court memorial files of the Qing Dynasty. Early accounts of weather phenomena are included in accounts recorded in the Oracle bones records.	(Zhang, 2004)	Meteorological Records of the Last 3,000 Years
308AD - 2000AD	Liaoning	The drought chapter of this book provides a description of the drought in Liaoning Province from 308 to 2000 AD. And from 352 to 2000 AD, there were descriptions of insect disasters, famine, epidemic diseases, and some unexplained disasters.	(Li and Meng, 2005)	China Meteorological Disasters Ceremony (Liaoning volume)
352AD - 1948AD	Liaoning	Based on historical data, drought descriptions and statistics were provided for the Liaoning area from 352 to 1948. For the 12 key cities in Liaoning Province (including Shenyang), the drought rating was listed by year. This drought level assessment was based on the reduction rate of grain yield. And a statistical table of light drought years and heavy drought years for several rivers in Liaoning area is provided.	(Office of State Flood Control and Drought Relief, 1999)	Liaoning Flood and Drought Disaster
1949 - 2000	China	It provides the annual and seasonal changes of agricultural drought, the change of disaster areas, the degree of drought risk, and the measures of drought prevention and mitigation against agriculture after 1949.	(Zhang, 2008)	China Historical Drought from 1949 to 2000
2000	Liaoning	This book provides the causes, characteristics and the degree of drought and the statistics of surface water resources in each region. The degree of drought in Liaoning Province in 2000 was respectively analysed by precipitation, river runoff, crop yield reduction and farmland drought rate, and comprehensive indicators.	(Pu, 2001)	Extraordinary drought in Liaoning Province during 2000
2001	Liaoning	Data and description of drought causes, precipitation distribution, and the multi-year comparison of the net flow of rivers are provided. The drought level is determined by the extent of agricultural disasters, meteorological factors, precipitation frequency, and water supply and demand balance.	(Wang, 2002)	Spring Drought Report of Liaoning Province in 2001
1986-2005	Shenyang	This multi-year Shenyang chronicle provided the major events that occurred in Shenyang from 1986 to 2005, including some meteorological disasters. The natural environment section records the climate, rainfall, and natural disasters during the period.	(Zou, 2010)	Shenyang chronicles 1986-2005, volume one
1994-2011	Shenyang	The annual Shenyang chronicle records the climatic conditions, meteorological disasters, and some water conservation measures of the year.	(Shenyang Municipal People's Government Local Records Office (1994-2011), 2011)	Shenyang chronicles 1994-2011 (separate volumes)
1276-1985	Shenyang	In integrate Shenyang chronicle, there are statistics on flood and drought in suburbs region, Xinmin region and Liaozhong region in Shenyang city from 1276-1985.	(Shenyang Municipal People's Government Local Records Office, 1998)	Shenyang chronicle, volume eight

1840-1987	Shenyang	The big events which happened in Shenyang from 1840 to 1987. In physical geography part, it described the seasonal climate and precipitation characters in Shenyang, and natural disasters.	(Meng, 1989)	Shenyang chronicles, Integrated volume one
1689 - 1911	China	This information comes from more than 1 million pieces of Qing dynasty memorial to the throne, including rain, floods, droughts, water conservancy projects.	(Tan, 2013)	Historical materials of drought archives in the Qing Dynasty

Table 2. Data Information Description Table

(Source 1: https://rda.ucar.edu/datasets/ds578.5/docs/ndp039.des; Source 2: NDRCC)

Source 1			Source 2			
Value	Meaning	Impacted record (%)	Value	Meaning	Treatment	Impacted record (%)
-9999	Error	0.83	32700	Microscale	Ignore	8.97
R	Total is identical to the previous or following month's total.	0.62	32744	Black	Ignore	0
H	Total is especially high for this station and is considered spurious	0	32766	Missing	Ignore	0
E	Original total was considered suspect too high for the station.	0	30xxx	Rain and snow	Keep	0.32
			31xxx	Snow	1/10	1.51
			32xxx	Fog frost	Ignore	9.25

Table 3. SPI drought classifications applied within different regions, a) China Grades of meteorological drought (National Standards of the People's Republic of China, 2017); b) the arbitrary drought intensity classes originally defined by Mckee et al. (1993); and, c) as used by the WMO (World Meteorological Organization (WMO), 2012).

Grade / class	A		B		C	
	SPI value	Drought level	SPI value	Drought level	SPI value	Drought level
1	0.49 to -0.49	Normal	0 to -0.99	Mild drought	-0.99 to 0.99	Near normal
2	-0.5 to -0.99	Mild drought	-1.00 to -1.49	Moderate drought	-1.0 to -1.49	Moderately dry
3	-1.00 to -1.49	Medium drought	1.50 to -1.99	Severe drought	-1.5 < to ≤ -1.99	Severely dry
4	-1.50 to -1.99	Severe drought	≤ -2.00	Extreme drought	≤ -2.00	Extremely dry
5	≤ -2.00	Extreme drought				

Table 4. Drought class and phenomenon comparison table

	Class 1: Normal	Class 2: Mild Drought	Class 3: Moderate Drought	Class 4: Severe Drought	Class 5: Extreme Drought
Meteorology	Less record or no record/ Hot weather	Less rain for several month / rain delay/ drought	No rain for several months / drought deviant, frequently or in a wide range	Heavy annual drought	Heavy drought lasting for several years
Agriculture	Soil a bit dry/ dust cover	Wheat a bit dry or slightly reduced/ soil very dry	Injury to crop field/ wheat seedling withered/ no seeding/ difficult farming/	No harvest	Long-term wide-range land dry and no harvest at all
Hydrologic		River or canal water level slightly reduced	Slight interruption of the river/ soil is not moist	Canal or land dry up	Long-term river dry up
Economic		Food price instability	Food price rise	Food price suddenly very expensive	Sell important items at a low price in exchange for food
Social Impact		Social complaints/ unrest	Displaced or loss of home/ famine/ lack of food/ people beg for food/ people living hard	Large number of displaced people/ heavy famine/ locusts as food/ death/ people snatch supplies	Corpses everywhere/ cannibalism/ selling children or women
Derived disaster		Locust disaster/ windy and haze/	Locust disaster affect traffic (people and horses)/ epidemic/ turbid red moon	Flying locust shading sky/ fire/ Plague epidemic/	Extensive epidemics

Table 5. The frequency of droughts in Shenyang since 1200 AD and associated drought class (see Table 4). The average drought reflects the average class achieved for each period.

Year	Average drought class	Number of droughts recorded	Class 1	Class 2	Class 3	Class 4	Class 5	Classes 1-3	Classes 4-5
1201-1300	2.5	4	0	2	2	0	0	4	0
1301-1400	2.3	3	0	2	1	0	0	3	0
1401-1500	2.6	14	0	7	6	1	0	13	1
1501-1600	2.6	17	0	9	5	3	0	14	3
1601-1700	2.5	6	0	3	3	0	0	6	0
1701-1800	2.1	7	0	6	1	0	0	7	0
1801-1900	3.1	12	0	9	3	0	2	12	2
1901-2000	2.4	74	23	16	21	9	5	60	14
2001-2015	2.9	14	2	4	3	3	2	9	5

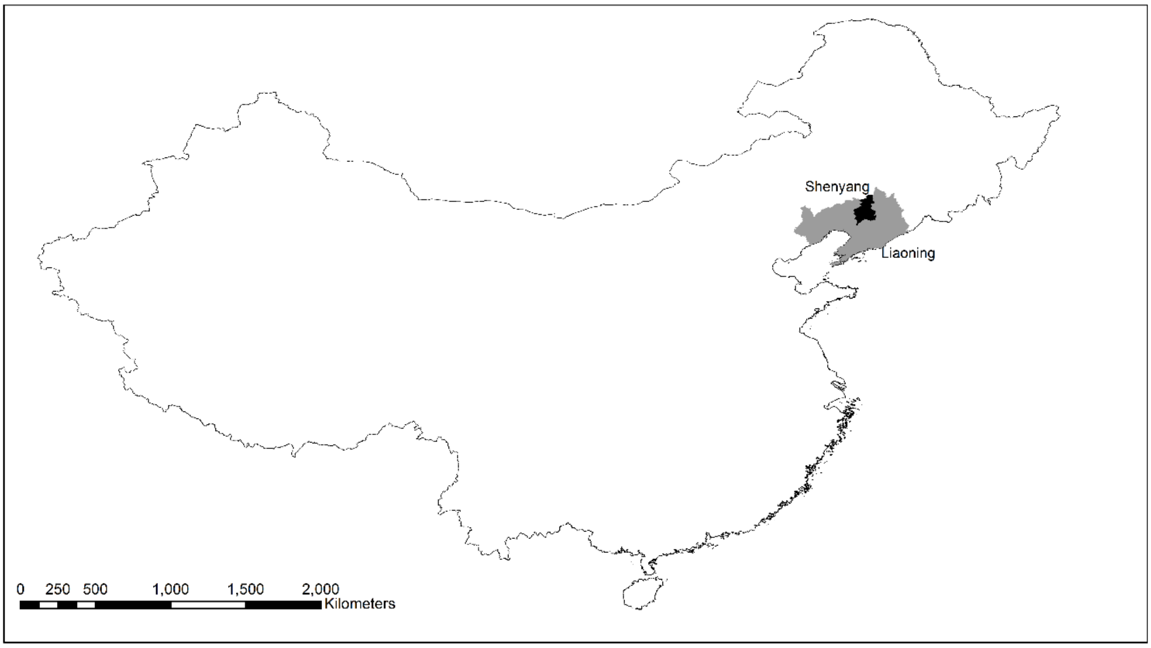


Figure 1. The geographical location of Shenyang, Liaoning Province and mainland China

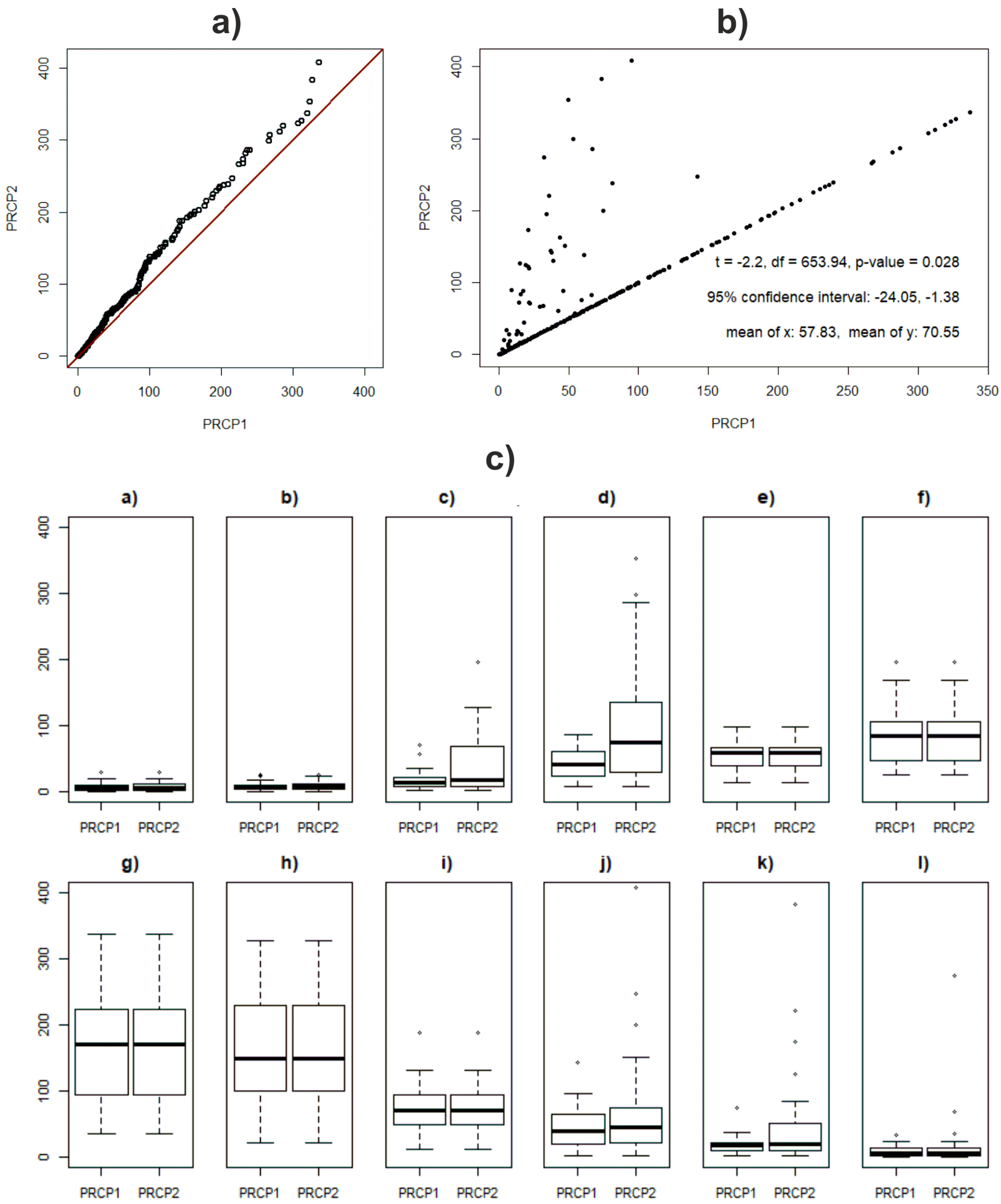


Figure 2. a) QQ plot of two precipitation (mm) data sources (p-value 0.028); b) monthly precipitation comparison of two datasets (significance Analysis of Precipitation from 1961 to 1988); c) monthly precipitation distribution and outliers (a-l: January to December)

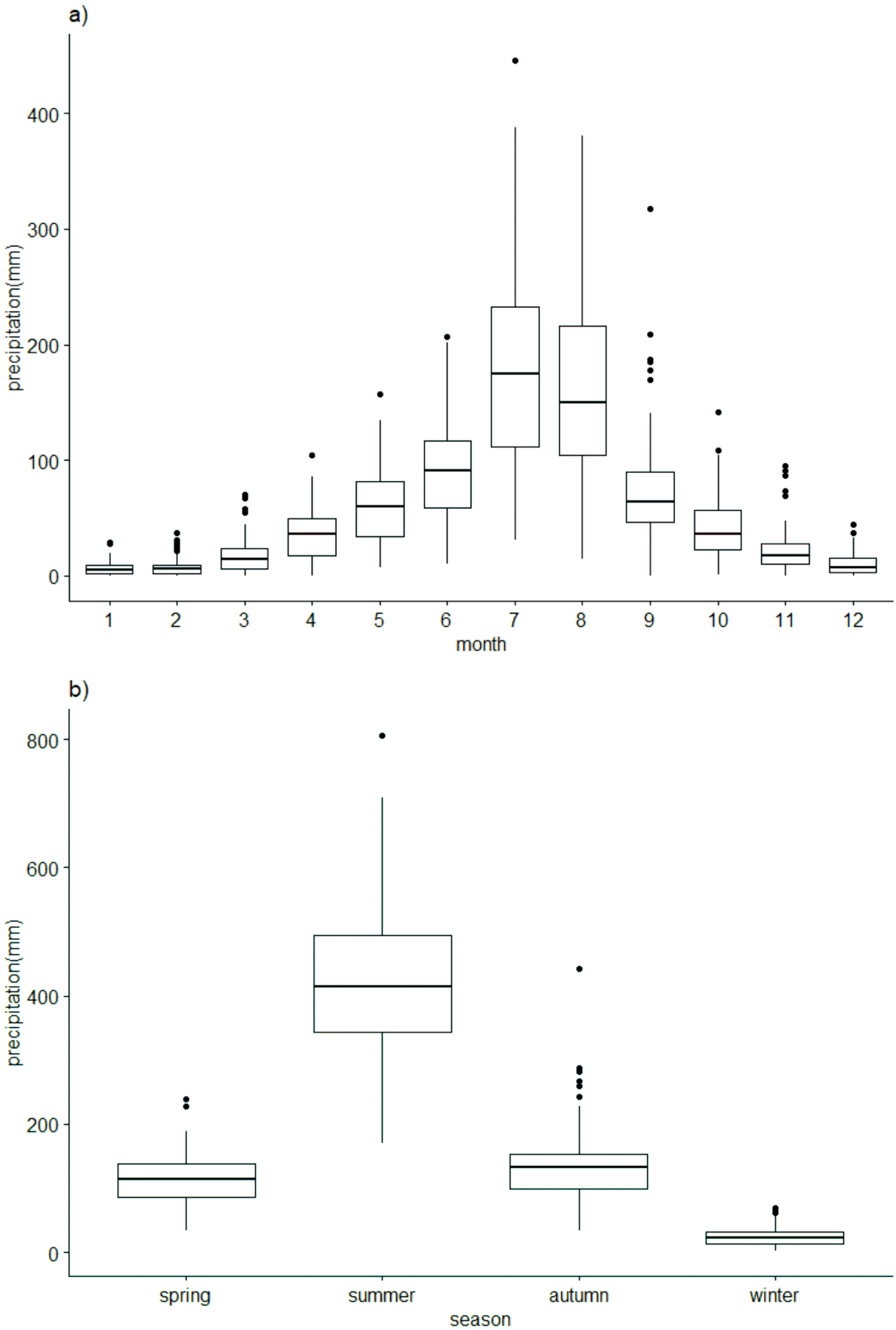


Figure 3. 1906-2015 Monthly and seasonal precipitation box chart

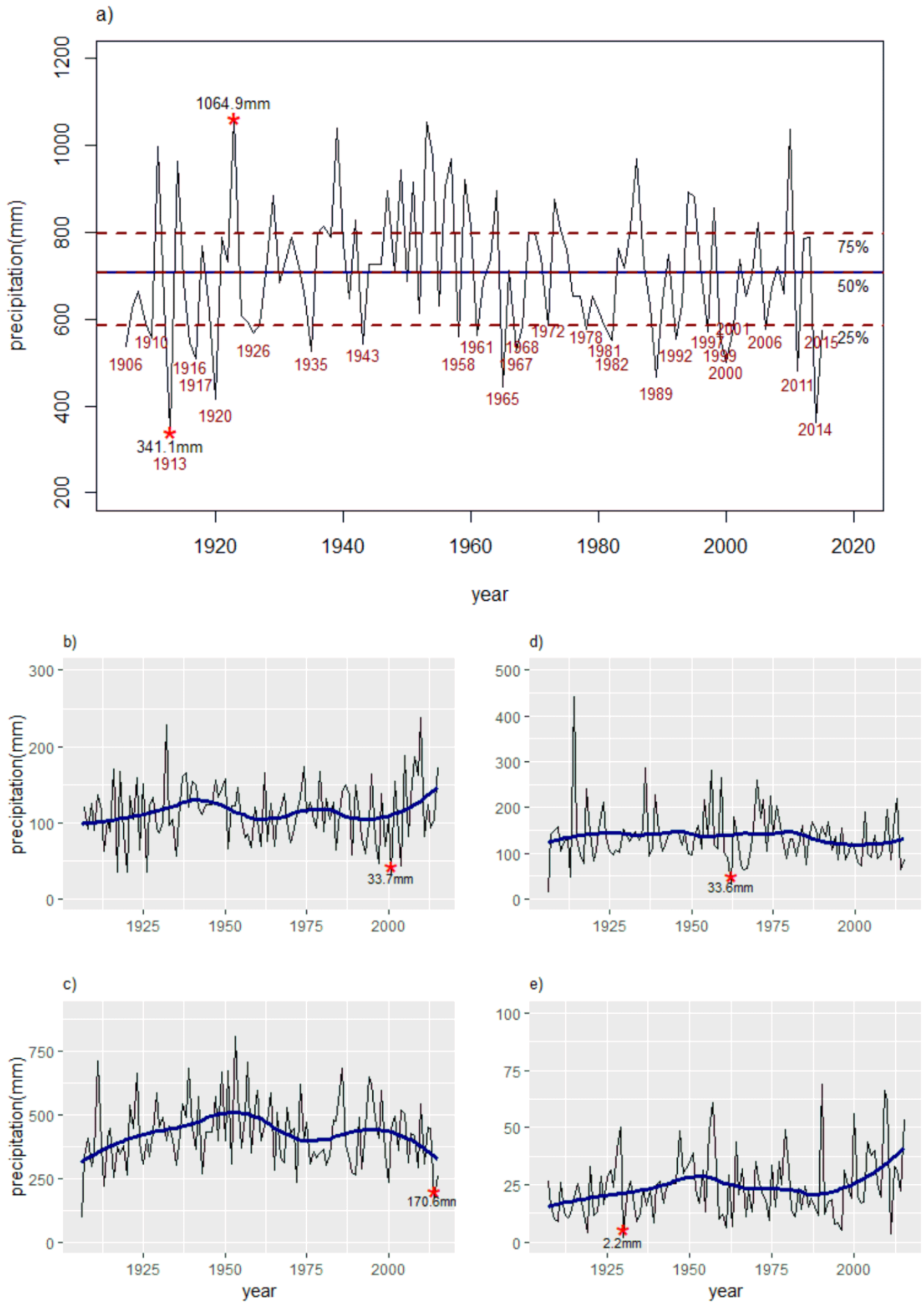


Figure 4. Annual and seasonal precipitation from 1906 to 2015, a) annual (quartiles indicated by dashed lines); b) spring; c) summer; d) autumn; and, e) winter. A 30-year Savitzky-Golay filter is presented (bold line b-e).

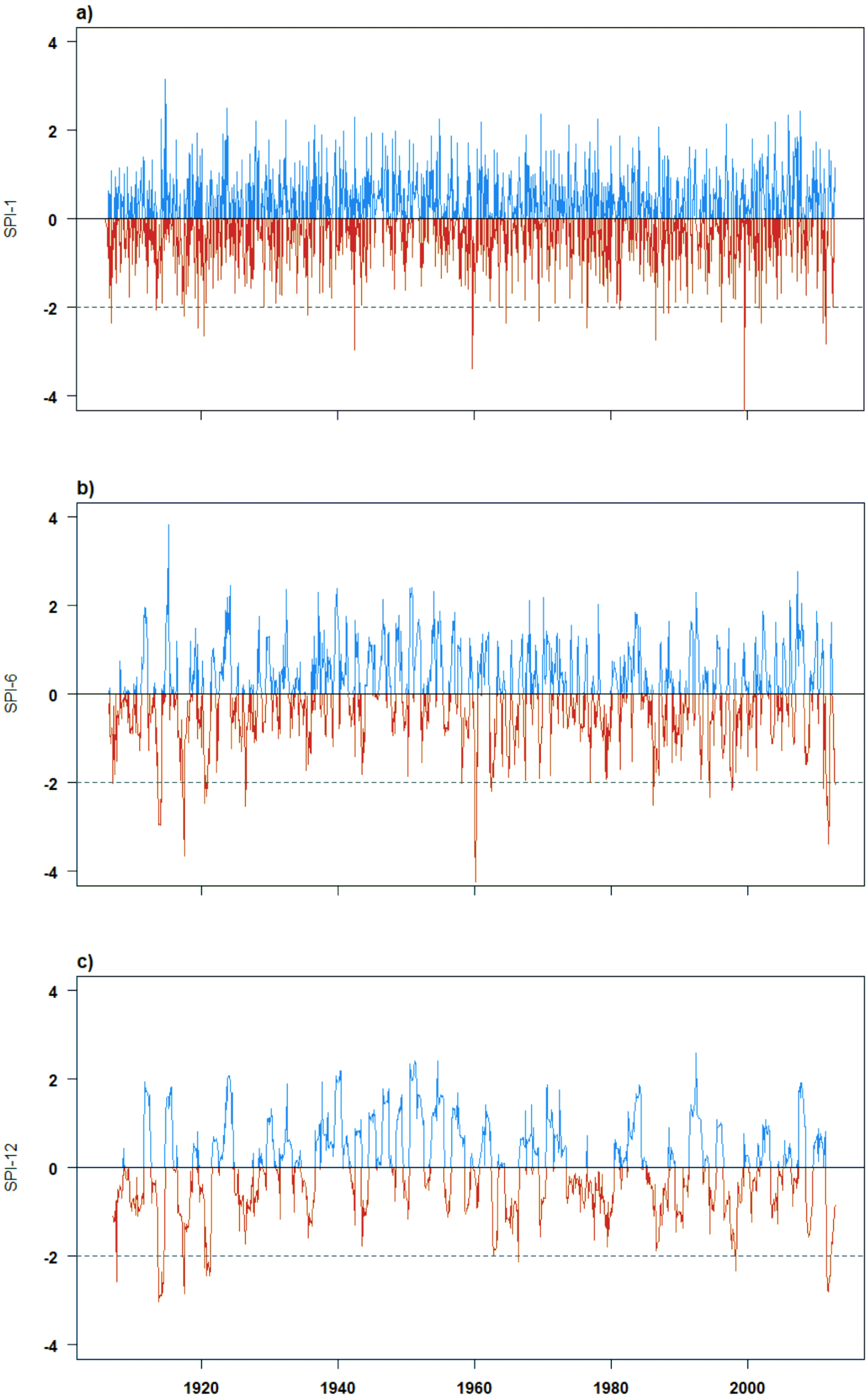
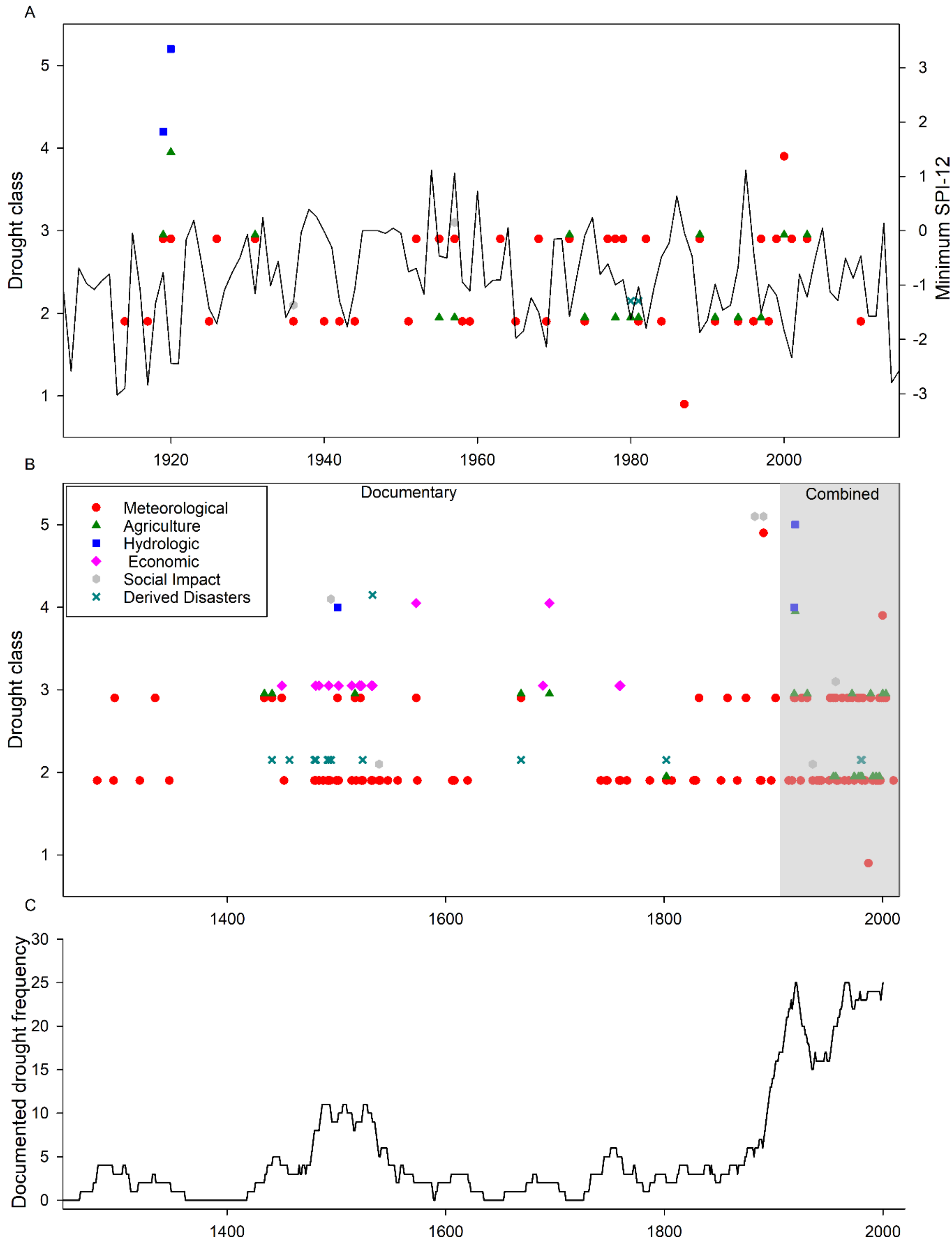


Figure 5. Standard Precipitation Index from 1906 to 2015, with wetter (blue) and drier (red) than normal conditions indicated for a): SPI-1; b) SPI-6; and, c) SPI-12



997
998 Figure 6. Shenyang drought classification (colour/shape) for a) combined archival and instrumental
999 period (1906-2015) with minimum annual SPI-12; b) augmented period (1200-2015); and, c) a
1000 running 30-year mean drought frequency (1200-2015).