



# Reassessing long-term drought risk and societal impacts in Shenyang, Liaoning Province, north-east China (1200–2015)

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**Abstract.** The occurrence of two severe droughts in north-east China since 2000 has raised attention in the risk presented by droughts. This paper presents a historic drought series for Shenyang in Liaoning Province, north-east China, from 1200 CE to the present with a reconstructed long precipitation series (1906–2015) augmented with historical documentary accounts. Analysis of the instrumental series using a standardized precipitation index (SPI) and extending it using historical records has produced a combined series spanning over 8 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 the early 20th century (i.e. 1907, 1916–1918 and 1920–1921), 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 20th century helped prevent the loss of life experienced during comparable severe droughts at the end of the 19th 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 organizations in responding to events.

## 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 difficult to predict and manage, with a variety of definitions in operational use around the world. There is no single universal definition defining what constitutes a drought, with a variety of definitions applied globally, with many focusing on a deficiency in precipitation over a period of time (Belal et al., 2014; Lloyd-Hughes, 2014; Wilhite, 2000). Droughts often develop slowly under natural conditions or through human intervention, causing adverse impacts on activities (e.g. food production) or societal groups (e.g. farmers) (Dai, 2011). Droughts often begin following a prolonged period of moisture deficiency (van Lanen, 2006; Palmer, 1965), propagating through the hydrological cycle, and exhibit differing spatial and temporal characteristics dependent on a variety of factors, such as antecedent conditions and soil moisture (Heim, 2002; Todd et al., 2013). Wilhite and Glantz (1985) classified droughts into four types: meteorological, hydrological, agricultural and socio-economic, with Mishra and Singh (2010) recommending the inclusion of a fifth classification – groundwater 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., 2009). Palmer (1965, p. 1) notes that “drought means various things to var-

ious 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 20th and 21st centuries, such as the 1930s Dust Bowl in the USA (Schubert et al., 2004); 1975–1976 in Europe (Parry et al., 2012; Zaidman et al., 2002); China in 1994 and 2010–2011 (Zhang et al., 2019), and South Africa in 2015–2017 (Wolski, 2018). Over recent decades, several studies have started to explore historical droughts (Brázdil et al., 2009, 2018b) and their associated impacts over timescales ranging from decades to centuries on water resources (Lennard et al., 2016), agriculture (Brázdil et al., 2018a), infrastructure (Harvey-Fishenden et al., 2019), stream and river flows (Zaidman et al., 2002), and groundwater (Bloomfield and Marchant, 2013). Recent calls (e.g. Trnka et al., 2018) in historical climatology have been for more analysis to be undertaken with existing data, particularly in understanding past socio-economic drought responses and changes in vulnerability. Considerable work has been undertaken in recent decades in developing robust 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 digitized sources has facilitated greater historical analysis (Black and Law, 2004; Wang et al., 2018) with increased recognition from regulatory authorities in 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) with droughts a recurrent feature of the Chinese climate (He et al., 2011). Droughts are considered to be the most disastrous natural hazard within China with over 465 000 deaths and more than 3.1 billion adversely affected from 1970 to the present and over 12 million deaths since 1900 (EM-DAT, 2019). Historically notable droughts in 1876–1878, 1928–1930 and 1958–1962 resulted in widespread loss of life and poor harvests, leading to serious social consequences including famine, robbery, unrest and political instability (De Châtel, 2014; Janku, 2018; Teklu et al., 1992; Yang et al., 2012). Between 206 BCE and 1948 CE, 1056 severe droughts were 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 globally advanced approaches applied during the early Qing Dynasty (1644–1912 CE) with both rainfall and snow depth recorded from 1736 to 1911 (Ge et

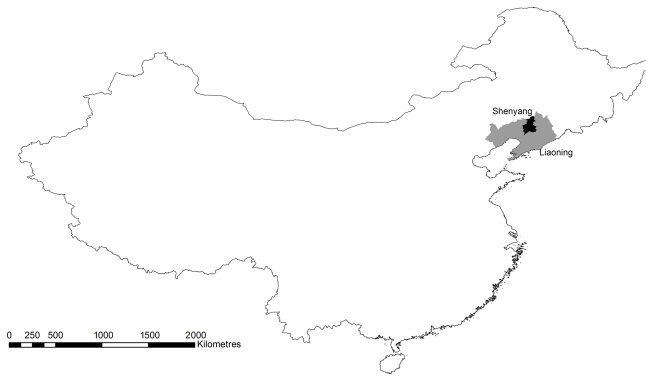
al., 2005). The installation of better equipment through the 1920s and 1950s saw many stations upgraded, with meteorological stations often retained; however, the availability of metadata on early recorders is limited. Past droughts have had a far-reaching impact on society in China; a clear understanding of current and future drought risk is therefore critical. With population growth, economic development, urbanization and climatic change, drought is a global challenge, and it poses a severe threat to food security, environmental ecology, and 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 north-east China. It considers the spatial and temporal variability of droughts, assesses drought characteristics, and examines drought-causing climatic conditions and the impacts of past droughts on society. Our objectives are as follows:

- i. to develop and analyse a record of droughts and associated impacts (1200 CE–present) for Shenyang using a variety of sources including documentary evidence and the compendium of Chinese droughts produced by Zhang (2004, 2013);
- ii. to identify and analyse contemporary droughts using instrumented daily precipitation series from the Shenyang Meteorological Observatory (Station 54342; 1961–2015) and to augment this series with the longer monthly precipitation data for Shenyang (1906–1988);
- iii. to generate a standardized precipitation index (SPI-1, -6 and -12) for the augmented precipitation series spanning the period 1906–2015, to construct one of the longest drought series (1200–present) in China by combining the augmented instrumental series (ii) with historical data (i), and then to classify the different types of drought and event severity;
- iv. to analyse 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 north-east China (Fig. 1) with a temperate continental monsoon climate and temperatures ranging from  $-17^{\circ}\text{C}$  (January) to  $29^{\circ}\text{C}$  (July) and decreasing from the south-west to the north-east (plain to mountain) (Chen et al., 2016), whilst average annual precipitation ( $500\text{--}1000\text{ mm yr}^{-1}$ ) increases from west to east (Zhang et al., 2013). The region has witnessed reductions (at 78 % of stations) in annual precipitation over the period 1961–2008 (Liang et al., 2011). The Shenyang municipality is home to approximately 8 million people in 2016. Liaoning



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

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 3000 Years*, produced by Zhang (2004) and updated in 2013, summarizes 7835 historical sources. These sources include the earliest existent materials in the Chinese language, the Oracle Bones collection (ca. 1600 BCE), through to more recent sources which describe meteorological incidences in China. The Oracle Bones collection 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, 2013) 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 Li and Meng (2005) provides detailed accounts of droughts, together with associated disasters including those potentially caused by droughts, such as famine and plague; a full list of source materials can be found in Table 1. Over recent decades considerable effort has focused on collating archival materials present across China that detail natural hazards, this wealth of information provides valuable opportunities for further exploration. However, such a high volume of material 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 clearly identified. Recent developments include a move to digitize 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 provides valuable auxiliary reference materials, including the following items: Shenyang local records (Meng, 1989; Shenyang Municipal People's Government Local Records Office (1994–2011), 2011) and 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 areas from 1949 to 1990 in Liaoning Province; statistics on drought area of heavy drought in Liaoning Province; drought rating assessments 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; and regular frequency of continuous drought in the dry season in Liaoning Province. Local newspapers have also been accessed to corroborate records of droughts, such as the Shengjing Times (Shenyang was previously called Shengjing; see Table S1 in the Supplement).

##### 3.1.2 Instrumental data

Instrumental climate data are taken from two datasets. The first is long-term meteorological data including monthly precipitation (May 1905 to December 1988) from the Research Data Archives Computational and Information Systems Lab (NCAR, 1996), no records are 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) and sunshine hours (V14032) for the period 1 January to 31 May 2016. This study uses the precipitation data (V13201). However, subsequent drought analyses could use additional meteorological variables for more complex drought modelling. Analysis of these two datasets permits a temporal analy-

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

Years	Location	Notes in material	Author/year	Source
23rd century BCE to 1911 CE	China	The collection of various weather, climate and atmospheric physical phenomena in history, including flood, drought, rain, snow, cold and warm weather, freezing, frost, and other records. There are 7835 kinds of historical materials used in the dataset, 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 3000 Years
308 CE to 2000 CE	Liaoning	The drought chapter of this book provides a description of the drought in Liaoning Province from 308 CE to 2000 CE. From 352 CE to 2000 CE, there are descriptions of insect disasters, famine, epidemic diseases and some unexplained disasters.	Li and Meng (2005)	China Meteorological Disasters Ceremony (Liaoning volume)
352 to 1948	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. A statistical table of light drought years and heavy drought years for several rivers in the Liaoning area is provided.	Office of State Flood Control and Drought Relief (1999)	Liaoning Flood and Drought Disaster
1949 to 2000	China	It provides the annual and seasonal changes in agricultural drought, the change in disaster areas, the degree of drought risk, and the measures of drought prevention and mitigation against agriculture after 1949.	Zhang et al. (2008b)	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 analysed by precipitation, river runoff, crop yield reduction, 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 to 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, Vol. 1
1994 to 2011	Shenyang	The annual Shenyang chronicle records the climatic conditions, meteorological disasters and measures of the year.	Shenyang Municipal People's Government Local Records Office (2011)	Shenyang chronicles, 1994–2011 (separate volumes)
1276 to 1985	Shenyang	In the integrated Shenyang chronicle, there are statistics on flood and drought in the suburban region, Xinmin region and Liaozhong region in Shenyang city from 1276 to 1985.	Shenyang Municipal People's Government Local Records Office (1998)	Shenyang chronicle, Vol. 8
1840 to 1987	Shenyang	The big events which happened in Shenyang from 1840 to 1987. In the physical geography part, it describes the seasonal climate and precipitation character in Shenyang and natural disasters.	Meng (1989)	Shenyang chronicles, Integrated volume one
1689 to 1911	China	This information comes from more than 1 million pieces of Qing dynasty memorials to the throne, including rain, floods, droughts and water conservancy projects.	Tan et al. (2013)	History of Drought Archives in the Qing Dynasty



sis of the reconstructed long-term precipitation series with a long overlap period ensuring a statistical comparison of the datasets can be made.

Previous studies have illustrated a strong relationship between droughts and El Niño–Southern Oscillation (ENSO) anomalies (Li et al., 2019; L. Zhang et al., 2018) for differing regions of China; however, many of these studies use relatively short series (1960–2015). The extended precipitation series (1906–2015 CE) presented here provides a valuable opportunity to explore this relationship over a longer timescale. The ENSO3.4 sea surface temperature index, defined as the area-averaged sea surface temperature (SST) anomalies over 5° N–5° S, 170–120° W 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 taken in assessing the historical record through the 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 province boundary (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 Dynasty, “Liao Dong Jun” was used for the Shenyang area. In contrast, 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 now the Sujiatun area in Shenyang (Wang and Pu, 2016); Yan (2012) detailed historical changes in the Shenyang area (Table S1).

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

- i. Information concerning the cause of the disaster or event location is unclear. For example, in 1549, a drought and locust disaster occurred in Xingcheng County in Liaoning Province (Ming Shi Lu Shi Zong Shi Lu, Vol. 353, No. 42). 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 with or related to droughts, such as locusts, epidemic disease or famine, when 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 Shi Lu Shi Zong Shi Lu, Vol. 378). The record does not explicitly state that a drought occurred, though this is a typical response to drought; therefore, the record is excluded.

### 3.2.2 Instrumental data

Data quality assessment and management of both long (NCAR) and shorter (NDRCC) series are required to ensure homogenization and data suitability (see Sect. 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 millimetres throughout. For both instrumental series, care and attention are 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 (January–February 1906, December 1908–January 1909 and December 1968–January 1969). There is a reduction of available meteorological data during the years 1943–1946 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, monthly averages are included when single months are missing as often local stations are also missing data. For the shorter instrumental daily precipitation series (NDRCC), data descriptors are included in Table 2, including the percentage of record impacted. The precipitation record for Shenyang has had 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. Correlation analysis of Shenyang with the nearby Benxi precipitation station record (~ 41 km south-east of Shenyang) demonstrates a stable difference (prediction ratio) 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 localized station relocation/instrument renewal, we consider the precipitation data at Shenyang to be homogeneous and reliable.

Analysis of the two series for the coeval years of record (1961–1988) was undertaken, and a Q–Q plot verified that both data sources are normally distributed (Fig. 2a). Figure 2b shows a 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 (October 1974); further examination reveals that all the variations occur in the period 1961–1979, with the two datasets producing identical values for all months from 1980 onwards; this replicability in

**Table 2.** Data information description table (source 1: <https://rda.ucar.edu/datasets/ds578.5/docs/ndp039.des>, last access: 10 April 2019; source 2: NDRCC).

Source 1			Source 2			
Value	Meaning	Impacted record (%)	Value	Meaning	Treatment	Impacted record (%)
–9999	Error	0.83	32 700	Microscale	Ignore	8.97
R	Total is identical to the previous or following month's total.	0.62	32 744	Black	Ignore	0
H	Total is especially high for this station and is considered spurious.	0	32 766	Missing	Ignore	0
E	Original total was considered suspiciously 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

the later records provides confidence in extending the NCAR dataset through to 2015. Analysis of the dispersion and outliers for each month was also undertaken (Fig. 2c), and the months with the greatest discrepancy are March and April, possibly reflecting challenges in the recording of snow/ice fall. A comparison of the monthly and seasonal precipitation patterns presented in Fig. 3 for Shenyang for the period 1906–2015 using the new augmented series identifies some abnormal values from the NDRCC data from the period 1961 to 1979 which appear unrealistic, e.g. April 1964, 285.9 mm with an average usually of ca. 50 mm. An analysis of the variability in the precipitation is presented (Fig. 4) with the lowest precipitation (the driest) (1913, 341.1 mm yr<sup>-1</sup>) and highest (wettest) years noted (1923, 1064.9 mm yr<sup>-1</sup>; Fig. 4a); a seasonal analysis and long-term trends are also presented (Fig. 4b–e) with a 30-year Savitzky–Golay filter (Savitzky and Golay, 1964).

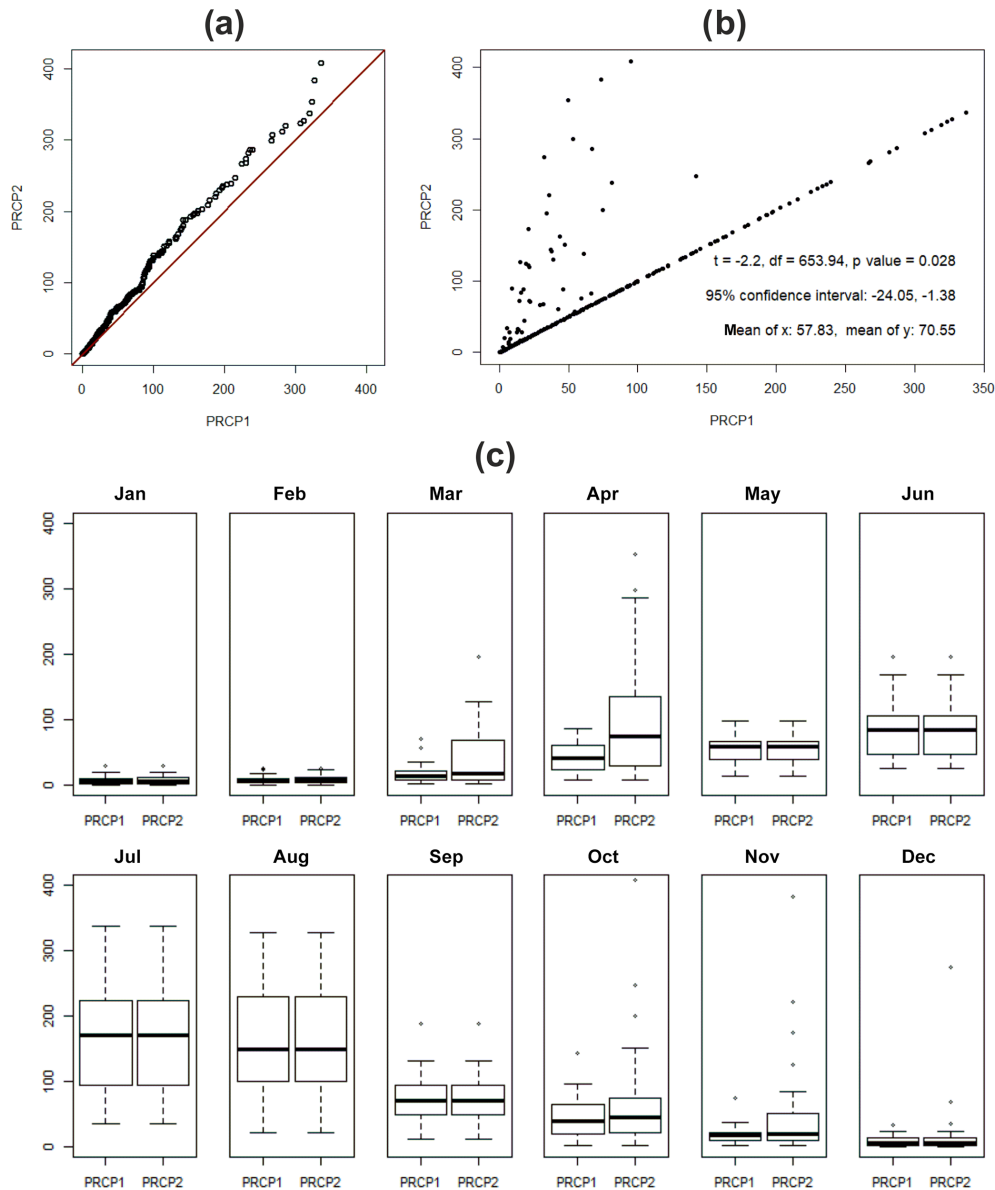
### 3.3 Drought identification

Using the combined instrumental and archival source materials, a record of droughts is reconstructed for Shenyang. The droughts are explored and examined from a number of perspectives, including type of drought (classification), intensity/magnitude, frequency and trends, which together characterize drought structure.

#### 3.3.1 Standardized precipitation index

There are several different drought indices that have been developed (Heim, 2002) which use a range of different input parameters. The long precipitation series reconstructed in this study only includes monthly data; therefore, the standardized precipitation index (SPI) is used as this index has several advantages when considered over long timescales

compared to other potential drought indices. 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., 2016; Mckee et al., 1993). The SPI developed by Mckee et al., (1993) is a widely applied meteorological drought index that quantifies precipitation deficits or excesses across different climates at multiple timescales, typically of 1–24 months. However, the simplicity of the SPI (precipitation is the only input) causes some limitations too, such as 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  $\leq 1$ . However, the National Standards of the People's Republic of China (2017) classification uses  $\leq -0.50$  as being indicative of drought onset, with drought termination identified as when SPI returns to  $\geq 0$  (Table 3a); within this study, we apply the classification as defined for China. The SPI can be used to characterize drought duration, severity and timing of onset and termination; together known as the drought structure (Noone et al., 2017). The SPI classification recommended in China (National Standards of the People's Republic of China, 2017) differs slightly from that of the World Meteorological Organization (WMO; 2012; Table 3a, c), though others have also proposed regionally specific SPI versions, such as Moreira et al. (2008) for Portugal. Drought duration is determined by the number of months between drought onset (SPI  $\leq -0.5$ ) and termination (SPI  $\geq 0$ ), and drought severity is categorized 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



**Figure 2.** (a) Q–Q plot of the two coeval precipitation series (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 for January to December.

(12 months) (Fig. 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 and calculating the cumulative probability. These are then converted into the standard normal distribution with the 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 distri-

butions have been recommended when a gamma distribution is not appropriate (Barker et al., 2016; Stagge et al., 2015).

### 3.3.2 Documentary analysis

Documentary data provide additional detail beyond that offered by instrumental series, adding valuable information reflecting both societal impacts and responses to past events (Pfister, 2010). At Shenyang, the first recorded drought occurs in 347 CE, 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.

**Table 3.** SPI drought classifications applied within different regions. (a) Chinese grades of meteorological drought (National Standards of the People’s Republic of China, 2017) and (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				

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 employed, such as Nash et al. (2016) who used a +2 to −2 classification in examining wet/dry phases in Natal and Zululand, South Africa. In augmenting the instrumental data with the historical series, clear benefits can be achieved if the descriptive classification is comparable to the SPI drought classification applied (Table 3a). Therefore, initially five drought classes are used in considering the historical descriptions, allowing alignment between the two data forms with typical types of descriptor for each of the five classes presented in Table 4.

Analysing the historical records unearthed different forms of drought impact which broadly reflect the five drought classes identified by Mishra and Singh (2010). Meteorological, hydrological and agricultural are comparable, the difference being that few accounts detail groundwater droughts within the historical records; as such, they are incorporated into hydrological droughts within this study. Socio-economic droughts are split into economic (impacts of precise cost) and social (impacts on people’s health, for example) impact. In dividing the socio-economic class into economic and social impact, we are responding to the wealth of historical materials present documenting drought impacts of this type. Each of the different classes of drought has varying degrees of 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), and others such as praying for rain/snow are associated with high classes (4/5), reflecting personal, communal 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 more robust analysis of interannual drought, a key feature in this paper over the long period analysed.

### 3.3.3 Drought trend and frequency analysis

The reconstructed drought series for Shenyang (1200–2015) permits an analysis of long-term drought trends and patterns. Over such long timescales, a number of socio-political and cultural changes have occurred (Bavel et al., 2019) which may influence 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 represent an essential underpinning in considering long-term drought trends and variability and are considered individually in each instance (see discussion by Brázdil et al., 2020).

An analysis of the different types of drought will be undertaken to assess long-term variability, severity and frequency, including an 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 through statistical analysis (Spearman’s  $p$  value – 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 characterized by the historical analysis, which is subjective, and that classified by the indices (SPI), which assumes a distribution with predefined probabilities attributed to each class (Guttman, 1998). Whilst an advantage in drought risk anal-



**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
Meteorological	Few records or no record/ hot weather	Less rain for several months/ rain delay/drought	No rain for several months/ extraordinary drought	Heavy annual drought	Heavy drought lasting for several years
Agricultural	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 dry land and no harvest at all
Hydrologic		River or canal water level slightly reduced	Slight interruption of the river/ soil is moist	Canal or land dries up	River dry for a long time
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/ heavy famine/ famine/lack of food/ people living hard	Large number of displaced people/ food/people beg for locusts as food/ death/people snatch supplies	Corpses everywhere/ cannibalism/selling children or women
Derived disaster		Locust disaster/ windy and haze	Locust disaster affects traffic (people and horses)/ epidemic/ turbid red moon	Flying locusts shading sky/ fire/plague epidemic/ epidemic/	Extensive epidemics

ysis, this makes the comparison to a subjective classification challenging.

## 4 Results and discussion

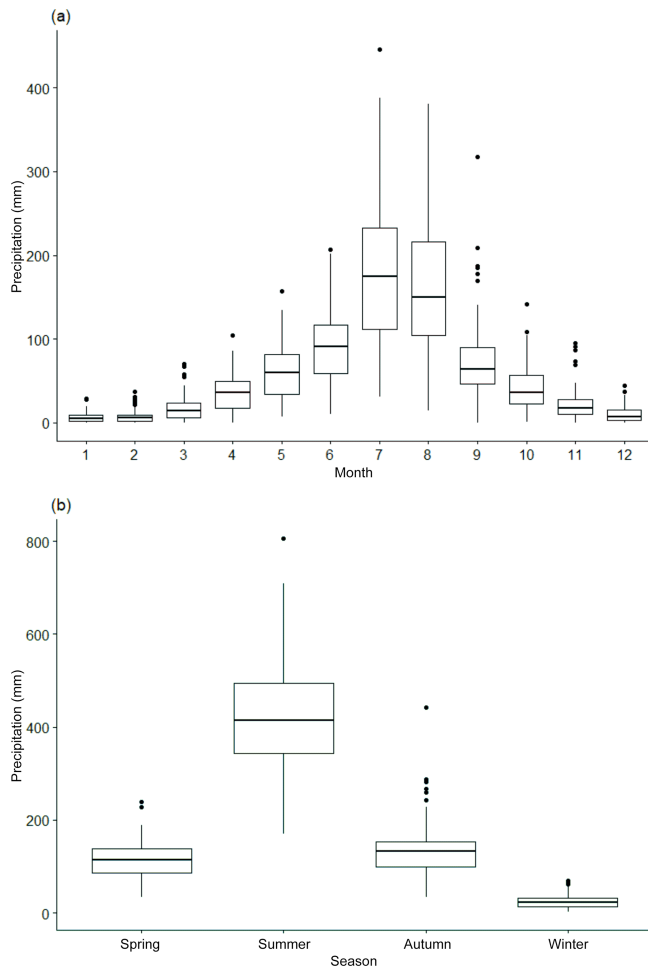
### 4.1 Temporal analysis of instrumental time series

The augmented precipitation series illustrates the range of precipitation experienced at Shenyang over the last 110 years with a maximum annual rainfall of 1064.9 mm (1923) and a minimum of 341 mm (1913). The mean of 704 mm is slightly higher than the median value (dashed red line; Fig. 4a). Of the 28 years of 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 (Fig. 3), which is typical of a continental climate. Documentary accounts often discuss spring droughts in Shenyang which hinder the development of crops at the start of the growing season (Wang et al., 2019).

Seasonal analysis of precipitation (1906–2015; Fig. 4b, e) illustrates that precipitation in winter and spring gradually increases with time with a slight reduction in summer and autumn precipitation, but all are statistically insignificant (at 0.05 level; Fig. 4c, d). The most severe spring drought occurred in 2001 with only 33.7 mm of 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 (170.6 mm) with precipitation less than 50 % of the norm presenting the worst summer drought since 1961; in response, the Liaoning provincial government instigated a level III drought emergency response, which included additional funding from the central government (CNY 150 million) and provincial departments (CNY 70 million) (Wang, 2014), with drought relief teams being 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, SPI-6 being appropriate for seasonal drought analysis and SPI-12 for annual to multi-annual droughts. SPI-6 with scores of  $\leq -2$  (severe droughts) occur 14 times during the 110-year record (Fig. 5b, 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-annual droughts. There are seven droughts that exceed  $\leq -2$  in the SPI-12 series (Fig. 5c).



**Figure 3.** (a) Monthly and (b) seasonal precipitation box charts for 1906–2015.

## 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 to 2015 with documentary (coloured) and instrumental data (black) for Shenyang (Fig. 6b). Analysis of the period 1906–2015 demonstrates that 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 records, 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 the absence of record often likely reflecting no drought; therefore, the analysis was repeated, and years with no de-

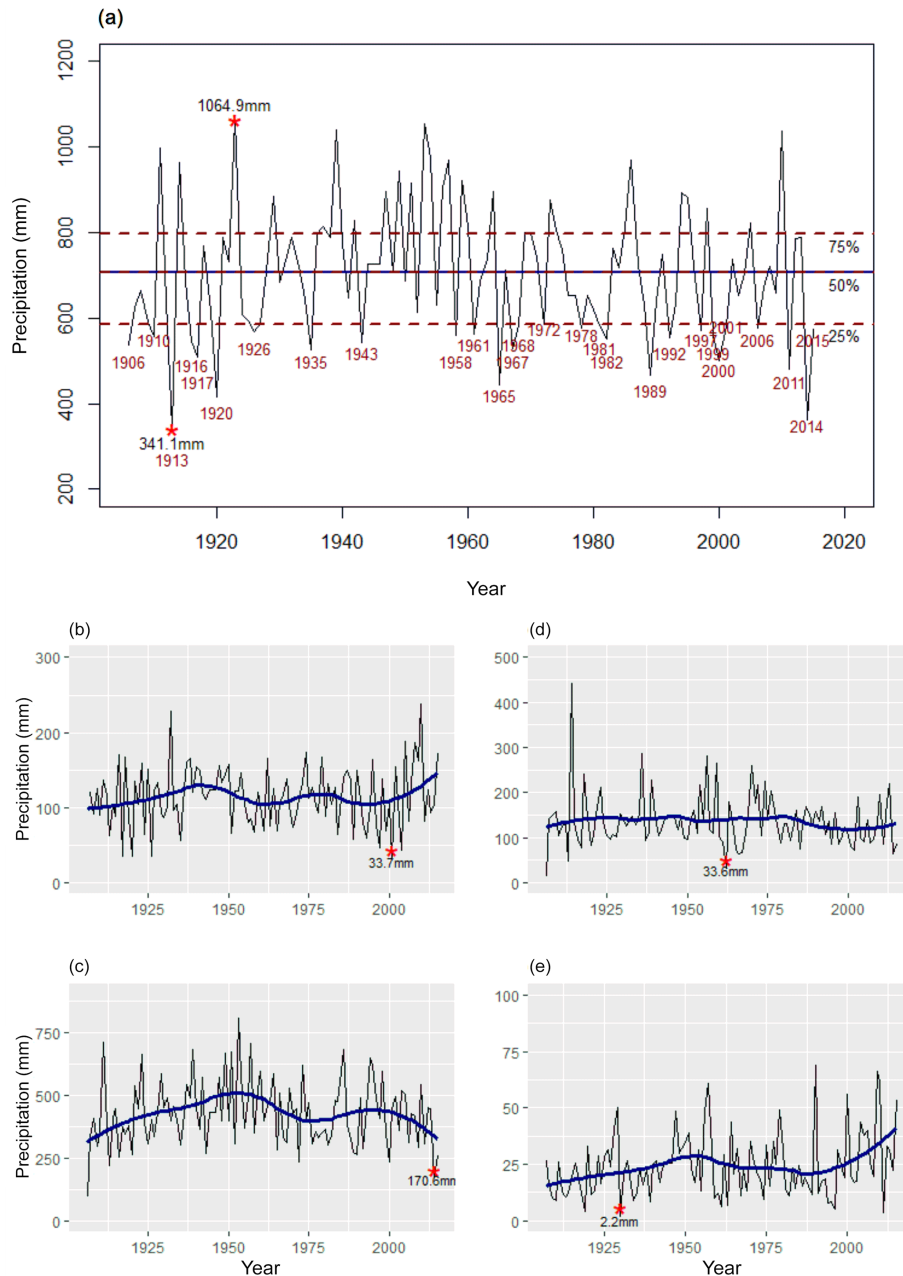
scription were attributed to class 1. As a result, a statistically significant relationship is identified (Spearman,  $p < 0.05$ ).

There are few early records from the 13th and 14th centuries; however, there is a small peak in Fig. 6c indicating that the region experienced increased droughts, and, as Li (2019, p. 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 15th and 16th centuries, and these events are evidenced across multiple drought types with several being class 3, including droughts in 1434 and 1450 and the class 4 drought of 1501, which are described as follows: “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 Shi Zong Shi Lu, Vol. 112, No. 41), “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 Ying Zong Shi Lu, Vol. 192, No. 10), 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 H. Zhang et al. (2018). This represents a notable drought-rich phase with multiple types of droughts recorded (Fig. 6b, c), and it also coincides with a mega-drought identified across much of Europe (Cook et al., 2015) and parts of North America (Cook et al., 2014), suggesting that this drought may have extended across more of the Northern Hemisphere than previously identified.

A relative quiescent phase is then noted between 1600 and 1750 with few droughts recorded (Fig. 6b). Several droughts are identified in the period 1750–1880 CE; however, the frequency and severity of droughts increase after that (Fig. 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 drought frequency from 1501 to 1600 and drought frequency then decreasing until the 19th century (Fig. 6c).

The frequency of class 5 drought events indicates an increase during the 20th century, but they are not evenly distributed with most (66%) occurring in the period 1906–1921 (1907, 1913–1914, 1916–1918 and 1920–1921) and with only three severe (SPI-12,  $< -2$ ) drought events after



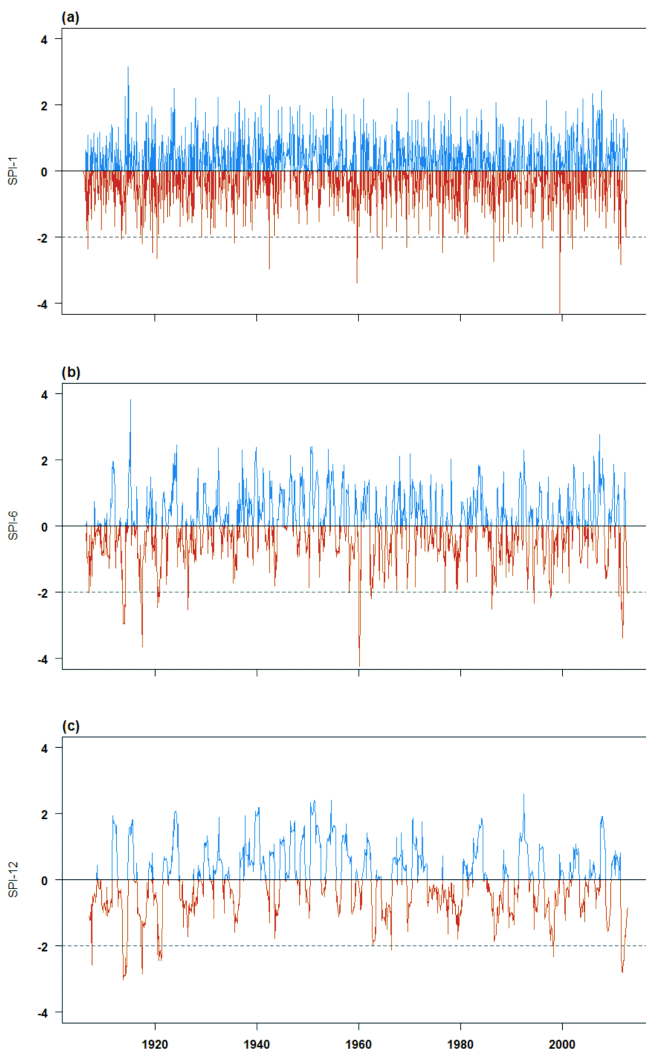
**Figure 4.** Annual and seasonal precipitation from 1906 to 2015: (a) annual (quartiles indicated by dashed lines), (b) spring, (c) summer, (d) autumn and (e) winter. A 30-year Savitzky–Golay filter is presented (bold line in b–e).

1921 in Shenyang in 1968–1969, 1999–2002 and 2014–2015 (Fig. 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 identified as classes 2 and 3 and few events classified as either 1, 4 or 5. However, the presence and magnitude of the early droughts in the period 1906–1921 are corroborated by 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 Fig. 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 the documented droughts in classes 2 and 3 (Fig. 6b). The absence of deaths being documented restricts the number of class 5 socio-economic droughts, although the drought of 1920–1921 is documented as a class 5 hydrological drought, the only documentary class 5 event in the 20th century. It may be that information detailing

**Table 5.** The frequency of droughts in Shenyang since 1200 and associated drought classes (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



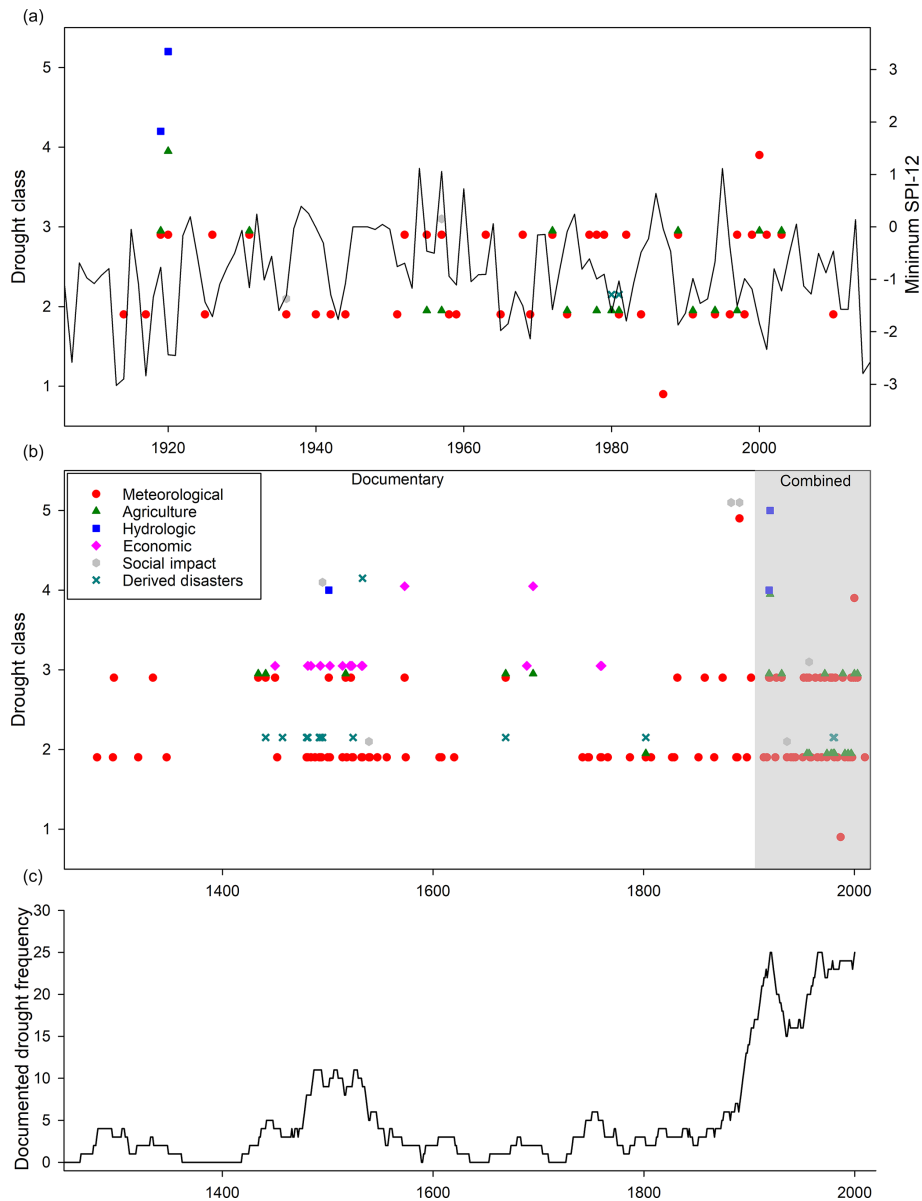
**Figure 5.** Standard precipitation index from 1906 to 2015, with wetter (blue) and drier (red) than normal conditions indicated for (a) SPI-1, (b) SPI-6 and (c) SPI-12.

the most severe aspects of past droughts was not published and/or that the droughts within Liaoning Province did not lead to such severe impacts as few events prior to the late 19th 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 on the provincial scale to incorporate a more extensive diversity of impact.

### 4.3 Societal vulnerability to droughts

The transformation of responses in Shenyang from *pre-industrial (folk)*, to *industrial (technological)* and subsequently to *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 20th century, namely 1907 ( $-2.6$ ), 1917 ( $-2.8$ ) and 1921 ( $-2.5$ ), illustrate how the responses and resulting impacts potentially changed. In analysing these events, the consequences of the droughts differed considerably; whilst they do not record deaths among the population in Shenyang and/or Liaoning Province, they are severe, with the 1920–1921 drought described as “spring drought for several months, well and river dries up, the land dries up, no harvest at all, winter disaster victims everywhere, people live in hunger, and could move out from the mountain village, village empty” (class 4 socio-economic drought but class 5-hydrological drought; 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 people being displaced (9 November 1920, p. 11); however, as Fuller (2011) importantly notes, this is often viewed from an international per-





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

spective, with local relief providers often failing to receive recognition. The responses to the drought varied but included those responses expected within an *industrial* framework, with both national and international relief occurring but also local support complementing *pre-industrial* responses, with the Shengjing Times (1920) reporting on 1 July that “Chief Zhang set up an altar begging for rain” (6080, p. 4). However, as Li (2007) notes in northern China, population increases during the late 19th century may have contributed to an increased susceptibility to drought-associated harvest fluctuations. In comparison, during the 2014 drought which resulted in a level III emergency response, itself a notable difference

from 1921 as a plan was in place, a number of responses were deployed to mitigate the impacts of the drought, and these included the provision of central and provincial relief funds (see Sect. 4.1), water transfer of 400 000 000 m<sup>3</sup> 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 supplying water to over 32 000 people suffering shortages (Wang, 2014). The impacts of the drought were widely reported in the media, with notable commentary focused on the impacts on water supplies and food production: “Food production in Liaoning ... estimated to decline by 5 billion kg this year” (China Daily, 2014). Whilst both

events, 1920–1921 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 had a relatively limited impact in Liaoning Province, with few accounts recording particularly notable impacts beyond reduced agricultural output, whereas, interestingly, the drought of August 1979 to July 1983, whilst not as 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 argument is further supported as the drought of July 1999 to April 2002 (SPI  $-2.3$ , duration 34 months) receives similar levels of documentary coverage to that of 1979–1983 and July 2014–2015 (SPI  $-2.8$ ; 18 months but extends beyond the end of the record) which 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 the previous dry 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 materializing 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 capitalizes on the long-term instrumental and documentary accounts available for Shenyang and Liaoning Province in NE China by constructing homogenized precipitation (SPI) series for 1906–2015 and a long documentary drought series for 1200–2015. Previously documented notable droughts in the early 20th century (1907, 1916–1918, 1920–1921) are compared to the droughts of the last 2 decades (1999–2002 and 2014–2015), illustrating that these have comparable drought structures with duration po-

tentially being more critical than the specific drought severity when considering the societal impacts. It illustrates that recent severe droughts (1999–2002 and 2014–2015), whilst notable, are not unusual within the region with several similar magnitude events in the early 20th century. Societally the most impactful droughts in the region occurred in the late 19th century (1883 and 1891) whilst appearing of comparable structure to those that occurred later (e.g. 1920–2021 and 2014–2015). However, the social and cultural circumstances of the late 19th century in the region resulted in more considerable social disruption and vulnerability. Reduced vulnerability to severe droughts is evident from the early 20th century as greater drought mitigation planning and central support are available (see responses to 1920–1921 and 2014–2015 droughts; Sect. 4.3). The relatively low number (one) of documentary accounts recording class 1 events reflects preferential recording of more notable events (classes 2–5). It remains challenging in any documentary analysis reconstructing climate as normal “mundane” conditions are often overlooked and therefore unrecorded. Further analysis is needed of the drought-rich phase identified around the start of the 16th century (Fig. 6c); whilst the impacts are not as prominent as those of the late 19th century, they are frequent and notable.

The calibration and augmentation of historical records with the instrumental series using the SPI present challenges. Whilst there appears to be a good agreement of drought classes 2–4, the probabilistic underpinning of the SPI inevitably ensures that 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 by the application of a long precipitation series, in which the potential of such events to be recorded increases. Analysis of the documentary droughts in the late 19th century suggests that the duration is comparable to those of the early 20th century, with similar generating mechanisms, dry winter and/or spring followed by a hard drought in summer, and a duration 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 to 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.

**Appendix A: Archival sources**

- Ming Shi, Zhi Di Liu, Wu Hang San, No. 10
- Ming Shi Lu Ying Zong Shi Lu, Vol. 192, No. 10
- Ming Shi Lu Shi Zong Shi Lu, Vol. 112, No. 41
- Ming Shi Lu Shi Zong Shi Lu, Vol. 353, No. 42
- Ming Shi Lu Shi Zong Shi Lu, Vol. 378

**Data availability.** The precipitation series are available from Table 1 (NCAR, 1996). The second series (1961–2015) of daily precipitation was supplied by the National Disaster Reduction Centre of China, and data use and access were permitted through their involvement in project NE/P015484/1.

**Supplement.** The supplement related to this article is available online at: <https://doi.org/10.5194/cp-16-1917-2020-supplement>.

**Author contributions.** LT undertook research, writing and analysis. NM, RC and HS supported LT in writing, data analysis and research approaches. NM, HS and RC were the PhD supervisors of LT at the University of Liverpool.

**Competing interests.** The authors declare that there is no conflict of interest.

**Special issue statement.** This article is part of the special issue “Droughts over centuries: what can documentary evidence tell us about drought variability, severity and human responses?”. It is not associated with a conference.

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