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

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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 the 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 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 (Lanen, 2006; Palmer, 1965), propagating through the hydrological cycle, exhibiting 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, 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, such as for example the 1930s 'Dust Bowl' in the USA (Schubert et al., 2004); 1975-76 in Europe (Parry et al., 2012; Zaidman et al., 2002); China in 1994 & 2010-2011 (Zhang et al., 2019) and South Africa in 2015-17 (Wolski, 2018). Over recent decades several studies have started to explored historical droughts (Brázdil et al., 2009, 2018b) and their associated impacts over timescales ranging from 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) and groundwater (Bloomfield and Marchant, 2013) Recent calls (e.g. Trnka et al., 2018) in historical climatology have called for more analysis to be undertaken

82 with existing data, particularly in understanding past socio-drought responses and changes in
83 vulnerability. Considerable work has been undertaken in recent decades in developing robust
84 long flood and drought chronologies, using combinations of archival (Brázdil et al., 2018b;
85 Yan et al., 2014; Zheng et al., 2006) and instrumental (Brázdil et al., 2009) sources from around
86 the globe; although much work to date has focused on Europe (Wilhelm et al., 2018). The
87 development of new online digitised sources has facilitated greater historical analysis (Black
88 and Law, 2004; Wang et al., 2018) with increased recognition from regulatory authorities in
89 the value of historical information (Kjeldsen et al., 2014).
90
91 China is one of the most natural disaster prone countries in the world (Dai, 2011; He et al.,
92 2011; Loorbach et al., 2011), with droughts a recurrent feature of the Chinese climate (He et
93 al., 2011). Droughts are considered as the most disastrous natural hazard within China, with
94 over 465,000 deaths and more than 3.1 billion adversely affected from 1970-present and over
95 12 million deaths since 1900 (EMDAT, 2019). Historically notable droughts in 1876-1878,
96 1928-1930 and 1958-62 resulted in widespread loss of life and poor harvests, leading to serious
97 social consequences including famine, robbery, unrest, and political instability (De Châtel,
98 2014; Janku, 2018; Teklu et al., 1992; Yang et al., 2012). Between BC 206 and AD 1948, 1056
99 severe droughts are recorded in Chinese history, though not spatially coherent (Zhang, 2004,
100 2013). In the period 1949-2000, Zhang et al. (2008b) identify ten years of 'heavy'(severe)
101 agricultural drought, and four years of 'extreme' agricultural drought. Precipitation recording
102 in China has developed through time, with some of the most globally advanced approaches
103 applied during the early Qing Dynasty (CE 1644-1912), with both rainfall and snow depth
104 recorded from 1736 to 1911 (Ge et al., 2005). The installation of better equipment through the
105 1920s and 1950s saw many stations upgraded, with meteorological stations often retained;
106 however, the availability of metadata on early recorders is limited. Past droughts have had a
107 far-reaching impact on society in China; a clear understanding of current and future drought
108 risk is therefore critical. With population growth, economic development, urbanisation and
109 climatic change, drought is a global challenge, but drought poses a severe threat to food security,
110 environmental ecology, urban and rural water supply in China (Bohle et al., 1994; Homer-
111 Dixon, 1994).
112
113 This paper examines the history of drought in the Shenyang region of Northeast China, it
114 considers the spatial and temporal variability of droughts, assesses drought characteristics

examines drought causing climatic conditions and the impacts of past droughts on society. Our objectives are:

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

    ii.   Identify and analyse contemporary droughts using 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) in China combining the augmented instrumental series (ii) with historical data (i), and then classify the different types of drought and event severity; and,

    iv.   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 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 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. 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.

149

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 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 high volumes 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 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 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); 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;

183   Comparison of Precipitation in Liaoning Province from 1949 to 1964 and from 1965 to 1990;

184   Comparison of grain yield per plant, drought frequency and drought reduction in various

185   regions of Liaoning Province; hydrological station data for Liaoning Province; regular

186   frequency of continuous drought in the dry season in Liaoning Province. Local newspapers

187   have also been accessed to corroborate records of droughts, such as the Shengjing Times

188   (Shenyang was previously called Shengjing – see Table S1).

189

190   3.1.2 Instrumental data

191   Instrumental climate data are taken from two datasets, the first is long-term meteorological

192   data, including monthly precipitation (05/1905 to 12/1988) from the Research Data Archives

193   Computational & Information Systems Lab (NCAR, 1996), no records are present for 1944-

194   1946. The precipitation records for Shenyang have also been viewed and photographed in the

195   Chinese Meteorological Archives in Beijing. The second precipitation series was retrieved

196   from the National Disaster Reduction Centre of China (NDRCC), which provides daily data

197   for air pressure (parameter code: V10004), daily average temperature (V12001), daily highest

198   temperature (V12052), daily lowest temperature (V12053), precipitation (V13201), average

199   wind speed (V11002), sunshine hours (V14032), for the period 01/01/1961 to 31/05/2016. This

200   study uses the precipitation data (V13201). However, subsequent drought analysis could use

201   additional meteorological variables for more complex drought modelling. Analysis of these

202   two datasets permits a temporal analysis of the reconstructed long-term precipitation series,

203   with a long overlap period ensuring a statistical comparison of the datasets can be made.

204

205   Previous studies have illustrated a strong relationship between droughts and ENSO anomalies

206   (Li et al., 2019; Zhang et al., 2018b) for differing regions of China; however, many of these

207   studies use relatively short series (1960-2015). The extended precipitation series (CE 1906-

208   2015) presented here provides a valuable opportunity to explore this relationship over a longer

209   timescale. The Niño 3.4 sea surface temperature index, defined as the area-averaged SST

210   anomalies over (5N–5S, 170–120W), compiled from PSD using the HadISST1 dataset for the

211   period 1870-2015 by Rayner et al., (2003) is used in this study.

212

213   **3.2 Data processing**

214   3.2.1 Documentary data

215 The compendium provided by Zhang (2004, 2013) provides the framework for the early record

216 (pre-1911); however, great care was undertaken in assessing the historical record through

217 verification of original accounts.

218

219 In the process of analysing documentary sources for Shenyang, it is necessary to pay particular

220 attention to historical changes to the name of Shenyang and the province boundary (see Table

221 S1). For example, in the book "Zhong Guo Dong Bei Yu Dong Bei Ya Gu Dai Jiao Tong Shi"

222 (Wang and Pu, 2016), it is noted that during the Han Dynasty, 'Liao Dong Jun' was used for

223 the Shenyang area. In contrast, during the Dong Han Dynasty, the southern part of Shenyang

224 continued to belong to Liao Dong Jun, and the northern part belonged to Xuan Tu Jun (Zhao,

225 2006). In addition, the Gao Xian region is now the Sujiatun area in Shenyang (Wang and Pu,

226 2016); Yan (2012) detailed historical changes in the Shenyang (Table S1).

227

228 Historical records for all drought years are included where records exist, but historical records

229 for the following situations are excluded:

230 i. Information unclear - the cause of the disaster or event location are unclear. For example,

231   in 1549, a drought and locust disaster occurred in Xingcheng County of Liaoning Province

232   ("Ming Shi Zong Shi Lu", Vol. 353). In 1549 Xingcheng belonged to Liaoxi; however,

233   Shenyang belonged to Liaodong. Therefore, this record is not in the target region and is

234   excluded.

235 ii. A record is excluded if it does not clearly state drought, or that a drought was the cause.

236   Although there are many types of event that are associated/related to droughts, such as

237   locusts, epidemic disease or famine, where historical records do not directly state drought

238   or attribute the cause to drought they are excluded. For example, in October 1551, the

239   Liaodong area did not collect grain tax because of disasters ("Ming Shizong Record", Vol.

240   3, 7:8). The record does not explicitly state that a drought occurred though this is a typical

241   response to drought, therefore the record is excluded.

242

243 3.2.2 Instrumental data

244 Data quality assessment and management of both long (NCAR) and shorter (NDRCC) series

245 are required to ensure homogenisation and data suitability (see section 3.1.2). Total

246 precipitation includes both liquid and equivalent frozen precipitation. All meteorological

247 variables are recorded as one-tenth of their specific units (mm) but are converted to mm

248 throughout. For both instrumental series, care and attention are taken with the original data

249   series quality, with the data descriptors recorded in Table 2. At Shenyang meteorological
250   station, missing data occurred eight times (representing 0.826% of the record), and rainfall was
251   marked three times with 'R', reflecting monthly totals identical to the previous month, raising
252   concerns as to the validity of the data (01-02/1906, 12/1908-01/1909 and 12/1968-01/1969).
253   There is a reduction of available meteorological data during the years 1943-46 following the
254   Second World War across much of eastern China, as such no suitable local sites could be
255   identified to infill this series; for other missing monthly data monthly averages are included
256   where single months are missing, as often local stations are also missing data. For the shorter
257   instrumental daily precipitation series (NDRCC), data descriptors are included in Table 2,
258   including the percentage of record impacted. The precipitation record for Shenyang has four
259   station relocations/instrument renewals during its monitoring record (October 1970, October
260   1976, January 1989 and June 2006). An analysis of the homogeneity of the record was
261   undertaken using the approach presented by Li et al. (2014) when assessing temperature
262   changes in Shenyang. Correlation analysis of Shenyang with the nearby Benxi precipitation
263   station record (~41 km southeast of Shenyang) demonstrates a stable difference (prediction
264   ratio) between the two series for all periods and an R^2 throughout of >0.88 (Table S2). In the
265   absence of any evident changes within the precipitation record resulting from localised station
266   relocation/instrument renewal, we consider the precipitation data at Shenyang to be
267   homogeneous and reliable.
268

269   Analysis of the two series for the coeval years of record (1961-1988) was undertaken, a Q-Q
270   plot verify that both data sources are normally distributed (Figure 2a). Figure 2b shows a linear
271   distribution (p-value of 0.028); however, differences between the series exist. During the period
272   1961-1988, the average difference between the two datasets is 12.72 mm, and the maximum is
273   313.2 (October 1974); further examination reveals that all the variations occur in the period
274   1961-1979, with the two datasets producing identical values for all months from 1980 onwards,
275   this replicability in the later records provides confidence in extending the NCAR dataset
276   through to the present (2015). Analysis of the dispersion and outliers for each month was also
277   undertaken (Figure 2c), the months with the greatest discrepancy are March and April, possibly
278   reflecting challenges in the recording of snow/ice fall. Comparison of the monthly and seasonal
279   precipitation patterns presented in Figure 3 for Shenyang for the period 1906-2015 using the
280   new augmented series identifies some abnormal values from the NDRCC data from the period
281   1961-1979, which appear unrealistic, e.g. 04/1964, 285.9 mm, with an average usually of c. 50
282   mm. An analysis of the variability in the precipitation is presented (Figure 4), with the lowest

283   precipitation (the driest, 1913: 341.1 mm a^{-1}) and highest (wettest) years noted (1923: 1064.9

284   mm a^{-1}; Figure 4a); a seasonal analysis and long term trend are also presented (Figure 4b-e)

285   with a 30-year Savitzky-Golay filter (Savitzky and Golay, 1964).

286

287   **3.3 Drought Identification**

288   Using the combined instrumental and archival source materials, a record of droughts is

289   reconstructed for Shenyang. The droughts are explored and examined from a number of

290   perspectives including: type of drought (classification), intensity/magnitude, frequency and

291   trends; which together characterise drought structure.

292

293   3.3.1 Standardized Precipitation Index (SPI)

294   There are a several different drought indices that have been developed (Heim, 2002), with these

295   using a range of different input parameters. The long precipitation series reconstructed in this

296   study only includes monthly data, therefore the Standardised Precipitation Index (SPI) is used

297   as this index has several advantages when used over long timescales compared to other

298   potential drought indices. Meteorological drought indicators can be divided into two categories

299   focused on either the physical mechanisms of drought, or the statistical distribution of

300   meteorological elements; the SPI belongs to the latter group and is widely used (Lennard et al.,

301   2015; Mckee et al., 1993). The SPI developed by Mckee et al., (1993) is a widely applied

302   meteorological drought index that quantifies precipitation deficits or excesses across different

303   climates at multiple timescales, typically of 1–24 months. However, the simplicity of the SPI

304   (precipitation is the only input) causes some limitations too, such as no consideration of

305   evaporative demand (Vicente-Serrano et al., 2014). SPI values are dimensionless units, with

306   negative values indicating drier than normal conditions and positive values wetter than normal

307   conditions. Drought onset is generally assumed to occur at SPI values exceeding ≤1. However,

308   the National Standards of the People's Republic of China (2017) classification uses ≤0.50 as

309   indicative of drought onset, with drought termination identified as when SPI returns to ≥0

310   (Table 3a); within this study, we apply the classification as defined for China. The SPI can be

311   used to characterise drought duration, severity and timing of onset and termination; together

312   known as the drought structure (Noone et al., 2017).= The SPI classification recommended in

313   China (National Standards of the People's Republic of China, 2017) differs slightly from that

314   of the WMO (2012; Table 3 (a and c), though others have also proposed regionally specific

315   SPI versions, such as Moreira et al. (2008) for Portugal. Drought duration is determined by

316   the number of months between drought onset (SPI ≤0.49) and termination (SPI ≥0), drought

317 severity is categorised using the SPI classification system with peak severity the minimum SPI

318 value recorded during the drought. Within this study, SPI will be examined at three temporal

319 scales SPI-1 (1 month), SPI-6 (6 months), and SPI-12 (12 months) (Figure 5a-c). The SPI was

320 determined by fitting a probability density function to selected accumulation periods using L-

321 moments to estimate parameters. A gamma probability density distribution was found to be the

322 most appropriate fit, using a Kolmogorov-Smirnov (K-S) test to compare empirical and

323 theoretical fit, calculating the cumulative probability. These are then converted into the

324 standard normal distribution, with the transformation of the cumulative probability of the fitted

325 distribution to standard normal distribution to define the SPI value (Lloyd-Hughes and

326 Saunders, 2002; Vicente-Serrano et al., 2010). Other univariate distributions have been

327 recommended where a gamma distribution is not appropriate (Barker et al., 2016; Stagge et al.,

328 2015).

329

330 3.3.2 Documentary analysis

331 Documentary data provides additional detail beyond that offered by instrumental series,

332 providing valuable information reflecting both societal impacts and responses to past events

333 (Pfister, 2010). At Shenyang, the first recorded drought occurs in 347 AD; but, only three

334 events are recorded during the period 347-1200; therefore the records analysed within this

335 paper start post-1200, as the frequency of records increases. Previous studies (e.g. Brázdil et

336 al., 2009; Hanel et al., 2018; Todd et al., 2013) using historical archival sources have examined

337 qualitative records and used a variety of different indices or grades of drought. The use of an

338 ordinal index systems for the classification of descriptive accounts in historical climatology is

339 common, with a range of classes used, such as . Nash et al., (2016) who used a +2 to -2

340 classification in examining wet/dry phases in Natal and Zululand in Southern Africa. In

341 augmenting the instrumental data with the historical series, clear benefits can be achieved if

342 the descriptive classification is comparable to the SPI drought classification applied (Table 3a).

343 Therefore, initially five drought classes are used in considering the historical descriptions,

344 allowing alignment between the two data forms, with typical types of descriptor for each of the

345 five classes presented in Table 4.

346

347 Analysing the historical records unearthed different forms of drought impact which broadly

348 reflect the five drought classes identified by Mishra and Singh (2010); meteorological,

349 hydrological and agricultural are comparable, the difference being few accounts detail

350 groundwater droughts within the historical records, as such they are incorporated into

351   hydrological droughts within this study. Socio-economic droughts are split into economic

352   (impacts of precise cost) and social impact (impacts on people, e.g. health). In dividing the

353   socio-economic class into economic and social impact, we are responding to the wealth of

354   historical materials present documenting drought impacts of this type. Each of the different

355   classes of drought has varying degrees of impact severity (Table 4), in documenting each of

356   these an assessment of the interrelationship between different types of impact can be made, for

357   example, the point at which food relief may be initiated, or tax payments suspended (typically

358   class 2/3), others such as praying for rain/snow are associated with high classes (4/5), reflecting

359   personal, community and governmental responses (e.g. government control of food prices).

360

361   Annual drought values for the instrumental period (1906-2015) are represented by the

362   minimum SPI-12 value within each calendar year; within the documentary accounts the most

363   severe class of drought is used to determine the classification. We opted to use the SPI-12 in

364   preference to SPI-6 (or shorter timescales), as precipitation in Shenyang has such a strong

365   seasonal skew toward the summer months. Use of SPI-12 also permits a more robust analysis

366   of interannual drought, a key feature in this paper over the long-period analysed.

367

368   3.3.3 Drought trend and frequency analysis

369   The reconstructed drought series for Shenyang (1200-2015) permits an analysis of long-term

370   drought trends and patterns. Over such long timescales a number of socio-political and cultural

371   changes have occurred (Bavel et al., 2019), which may influence the capacity a population to

372   respond to a drought of any given magnitude or severity (Keenan and Krannich, 2010; Kreibich

373   et al., 2019; Mechler and Bouwer, 2015). Human interventions may mitigate and/or exacerbate

374   the impacts of drought downstream, through hydrological system management and engineering

375   (He et al., 2017). The socio-political and cultural circumstances during each recorded drought

376   represent an essential underpinning in considering long-term drought trends and variability and

377   are considered individually in each instance (see discussion by Brázdil et al., 2020).

378

379   An analysis of the different types of drought will be undertaken, assessing long term variability,

380   severity and frequency, including examination of where droughts have been documented

381   during the instrumental period. The severity of droughts will be considered using the different

382   classes of drought, examining whether any notable differences in drought type emerge, which

383   may help determine underlying changes in vulnerability through time. The reliability of the

384   historical account classification process was assessed for the period 1906-2015 by statistical

385 analysis (Spearman - ordinal drought class) of the assigned drought class to annual minimum

386 SPI.

387

388 The principal challenge identified within this study is in attempting to assess droughts defined

389 between those characterised by the historical analysis which is subjective and that classified by

390 the indices (SPI), which assumes a distribution with predefined probabilities attributed to each

391 class (Guttman, 1998). Whilst an advantage in drought risk analysis, this makes it challenging

392 for comparison to a subjective classification.

393

394 **4 Results and Discussion**

395 **4.1 Temporal analysis of instrumental time series**

396 The augmented precipitation series illustrates the range of precipitation experienced at

397 Shenyang over the last 110 years, with a maximum annual rainfall of 1064.9mm (1923) and a

398 minimum of 341mm (1913). The mean of 704 mm is slightly higher than the median value (red

399 dashed line; Figure 4a). Of the 28 years annual rainfall below the quartile, ten occur prior to

400 1960 and 18 after. Precipitation at Shenyang is concentrated in the summer months, with little

401 winter precipitation (Figure 3), typical of a continental climate. Documentary accounts often

402 discuss spring droughts in Shenyang, which hinders the development of crops at the start of the

403 growing season (Wang et al., 2019).

404

405 Seasonal analysis of precipitation (1906-2015: Figure 4b & 4e) illustrates that precipitation in

406 winter and spring gradually increases with time, with a slight reduction of summer and autumn

407 precipitation, but all are statistically insignificant (at 0.05 level; Figure 4c and d). The most

408 severe spring drought occurred in 2001, with only 33.7mm spring precipitation, this is

409 supported with widespread media coverage of the drought in Shenyang and more widely in

410 Liaoning. The worst summer drought occurred in 2014 (170.6mm), with precipitation less than

411 fifty percent of the norm, presenting the worst summer drought since 1961; in response, the

412 Liaoning provincial government instigated a level III drought emergency response, this

413 included additional funding from central government (150 million yuan) and provincial

414 departments (70 million yuan) (Wang, 2014), with drought relief teams created to support

415 community water infrastructure projects (Sun, 2015).

416

417 The SPI generated from the long precipitation series is analysed at SPI-1, -6 and -12, with SPI-

418 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 the 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 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 1600-1750, with few droughts recorded (Figure 6b). Several droughts are identified in the period 1750-1880 AD; however, the frequency and severity of droughts increases after that (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 are not evenly distributed with most (66%) 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

485 period 1906-2015 provide valuable corroborative evidence when compared to the annual

486 minimum SPI-12 data, with most documentary accounts identified as class 2 and 3, with few

487 events classified as either 1, 4 or 5. However, the presence and magnitude of the early droughts

488 in the period 1906-21 are corroborated with documentary accounts classed as 4 and 5, with

489 documentary evidence in 2002 also supporting a class 4 drought.

490

491 The types of drought recorded within the records are indicated in Figure 6b, these illustrate that

492 the majority of records document meteorological drought conditions, followed by economic

493 impacts. The drought severity in the descriptive accounts' places most of the documented

494 droughts in class 2 and 3 (Figure 6b). The absence of deaths being documented restricts the

495 number of class 5 socio-droughts, although the drought of 1920-21 is documented as a class 5

496 hydrological drought, the only documentary class 5 event in the twentieth century. It may be

497 that information detailing the most severe aspects of past droughts was not published, and/or

498 that the droughts within the Liaoning province did not lead to such severe impacts, as few

499 events prior to the late nineteenth-century approach class 5. In focussing on the city of

500 Shenyang, there is also a risk that the impacts differed within the city to those experienced in

501 rural communities within the province, thereby reducing the number of agricultural droughts

502 documented. Future works should, therefore, focus at the provincial scale to incorporate a more

503 extensive diversity of impact.

504

505 **4.3 Societal vulnerability to droughts**

506 The transformation of responses in Shenyang from *pre-industrial* (*folk*), to *industrial*

507 (*technological*) and subsequently *post-industrial* (Chester et al., 2012; White, 1974) during the

508 period of study presents challenges in assessing and comparing impacts. Recent droughts of

509 comparable meteorological severity, e.g. 2014 (SPI-12: -2.8) to those of the early twentieth

510 century, namely 1907 (-2.6), 1917 (-2.8) or 1921 (-2.5) illustrate how the responses and

511 resulting impacts potentially changed. In analysing these events the consequences of the

512 droughts differed considerably, whilst they do not record deaths among the population in

513 Shenyang and/or Liaoning province they are severe, with the 1920-21 drought described as

514 "Spring drought for several months, well and river dries up, the land dries up, no harvest at all,

515 winter disaster victims everywhere, people live in hunger, and coild move out from the

516 mountain village, village empty" [class 4 socio-drought but class 5-hydrological] (Office of

517 State Flood Control and Drought Relief, 1999, p.388), across China an estimated 500,000

518 people died (Edwards, 1922). Analysis of the international media at the time reporting on the

519 event is shaped by the socio-political circumstances, with The Times (London) recording 3
520 million as being displaced (9 Nov. 1920 p.11); however, as Fuller (2011) importantly notes this
521 is often viewed from an international perspective, with local relief providers often failing to
522 receive recognition. The responses to the drought varied but included those responses expected
523 within an *industrial* framework, with both national and international relief occurring, but also
524 local support complimenting *pre-industrial* responses, with the Shengjing Times (1920)
525 reporting on the 1st July that "Chief Zhang set up an altar begging for rain" (6080, p.4).
526 However, as Li (2007) notes in north China, population increases without apparent agricultural
527 intensification or expansion during the late nineteenth century may have contributed to an
528 increased susceptibility to drought associate harvest fluctuations. In comparison, during the
529 2014 drought which resulted in a Level III emergency response, itself a notable difference from
530 1921 as a plan was in place, a number of responses were deployed to mitigate the impacts of
531 the drought, and these included: the provision of central and provincial relief funds (see section
532 4.1); water transfer of 400,000,000 m^3 from the Hun River, securing domestic and agricultural
533 provisions (Sun, 2015); and the provision of relief service teams to support local infrastructure
534 improvements, e.g. drilling new wells and supply of water to over 32,000 people suffering
535 shortages (Wang, 2014). The impacts of the drought were widely reported in the media, with
536 notable commentary focused on the impacts to water supplies and food production: "Food
537 production in Liaoning… estimated to decline by 5 billion kg this year" (China Daily, 2014).
538 Whilst both events 1920-21 and 2014 were severe droughts, the relief planning and coordinated
539 effort coupled with improved infrastructure and a more stable socio-political environment
540 facilitated a more efficient response.
541

4.4 Contemporary droughts and generating mechanisms

543 Analysis of contemporary droughts through coupled documentary sources and SPI provide
544 valuable insights into the importance of drought severity and duration on associated impacts.
545 The 'severe drought' as defined by the SPI of 1968 (SPI-12: -2.13, duration 26 months) appears
546 to have a relatively limited impact in Liaoning province, with few accounts recording
547 particularly notable impacts beyond reduced agricultural output, whereas, interestingly, the
548 drought of 08/1979-07/1983, whilst not as severe from the perspective of the SPI (-1.8), but of
549 longer duration (47 months) receives greater coverage within the documentary accounts,
550 possibly reflecting the duration and cumulative impact on agriculture. This argument is further
551 supported as the drought of 07/1999-04/2002 (SPI -2.3, duration 34 months) receives similar

552 levels of documentary coverage to that of 1979-83 and 07/2014-15 (SPI -2.8; 18 months, but
553 extends beyond the end of the record) which also receives more detailed descriptions.

554

555 Documentary accounts often identify that droughts begin in the spring months, but the SPI
556 results suggest that deficits often appear in the previous late summer (e.g. 1968-1969 and 1999-
557 2002 droughts), suggesting that the impacts of previous dry summer and/or autumn are not
558 particularly noted within the documentary accounts, and it is only when the impacts are felt
559 that the consequences are noted. Analysis of the seasonal precipitation to the seasonal ENSO3.4
560 series shows no significant correlations, but annual minimum SPI has a significant (95% level)
561 correlation with ENSO3.4 Summer (p= 0.0168) and Autumn (p= 0.0228) for the period 1906-
562 2015. This may be explained by the accumulated SPI-12, which reflects a long term deficit,
563 resulting in the severest elements of the drought materialising in summer/autumn; therefore,
564 the correlation with summer and autumn ENSO3.4 is a reflection of a longer lagged drought
565 accumulation process.

566

567 **5 Summary**
568 Our analysis capitalises on the long-term instrumental and documentary accounts available for
569 Shenyang and Liaoning province in NE China, by constructing homogenised precipitation (SPI)
570 series for 1906-2015, and a long documentary drought series 1200-2015. Previously
571 documented notable droughts in the early twentieth century (1907, 1916-18, 1920-21) are
572 compared to the droughts of the last two decades (1999-2002 and 2014-15), illustrating that
573 these have comparable drought structures, with duration potentially being more critical than
574 the specific drought severity when considering the societal impacts. It illustrates that recent
575 severe droughts (1999-2002 and 2014-15), whilst notable, are not unusual within the region,
576 with several similar magnitude events in the early twentieth century. Societally the most
577 impactful droughts in the region occurred in the late nineteenth century (1883 and 1891), whilst
578 appearing of comparable structure to those that occurred later (e.g. 1920-21 and 2014-15).
579 However the social and cultural circumstances of the late nineteenth century in the region
580 resulted in more considerable social disruption and vulnerability. Reduced vulnerability to
581 severe droughts is evident from the early twentieth century as greater drought mitigation
582 planning and central support are available (see responses to 1920-21 and 2014-15 drought,
583 section 4.3). The relatively low number (one) of documentary accounts recording class 1 events
584 reflects preferential recording of more notable events (class 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 sixteenth century (Figure 6c), whilst the impacts are not as prominent 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 present challenges. Whilst there appears to be a 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, dry winter and/or spring followed by a hard drought in 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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626

627 **Competing Interests**

628 None

629

630 **Author Contribution**

631 LT undertook research, writing and analysis; NM, RC and HS supported LT in writing, data

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946 **Archival sources**

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

950 Ming Shi Zong Shi Lu, Vol. 353

951 Ming Shi Zong, Vol. 3, 7:8

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954   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

955

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

960   Table 3. SPI drought classifications applied within different regions, a) China Grades of
961   meteorological drought (National Standards of the People's Republic of China, 2017); b) the arbitrary
962   drought intensity classes originally defined by Mckee et al. (1993); and, c) as used by the WMO
963   (World Meteorological Organization (WMO), 2012).
964

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				

965

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

970   Table 5. The frequency of droughts in Shenyang since 1200 AD and associated drought class

971   (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

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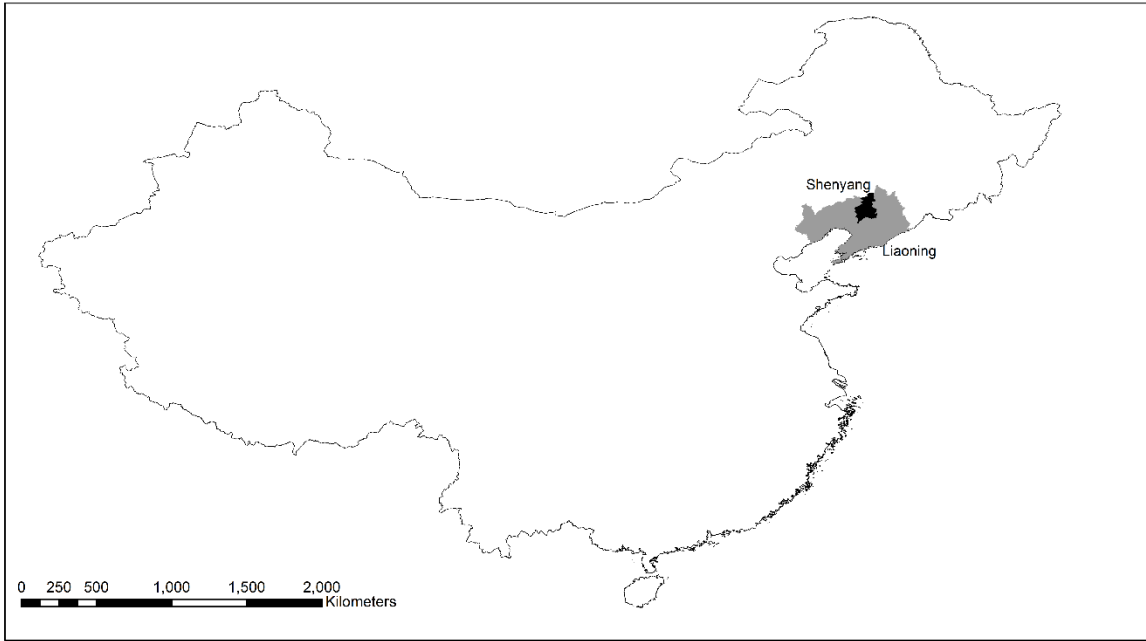
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975   Figure 1. The geographical location of Shenyang, Liaoning Province and mainland China
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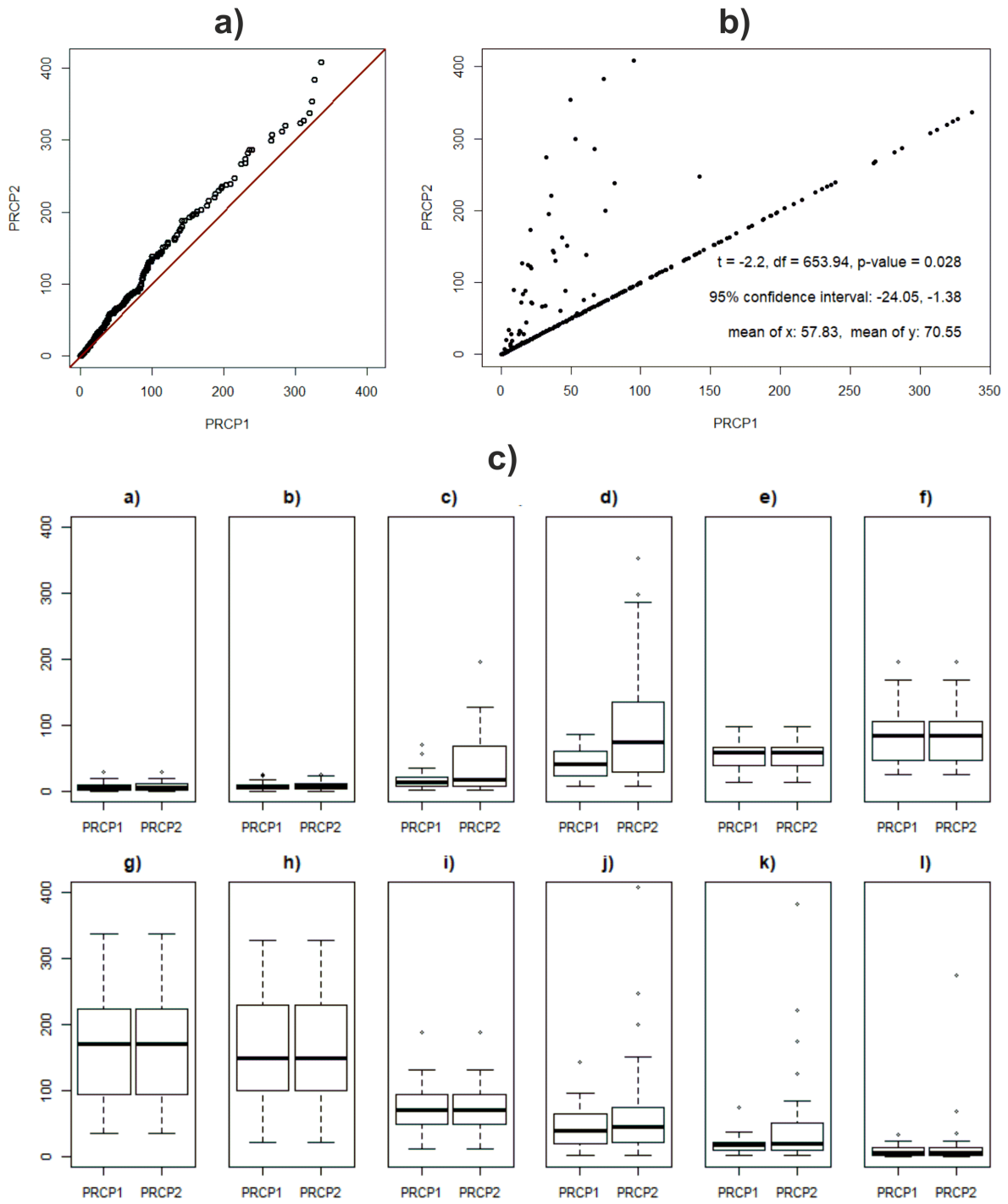
981   Figure 2. a) QQ plot of two precipitation (mm) data sources (p-value 0.028); b) monthly

982   precipitation comparison of two datasets (significance Analysis of Precipitation from 1961 to

983   1988); c) monthly precipitation distribution and outliers (a-l: January to December)

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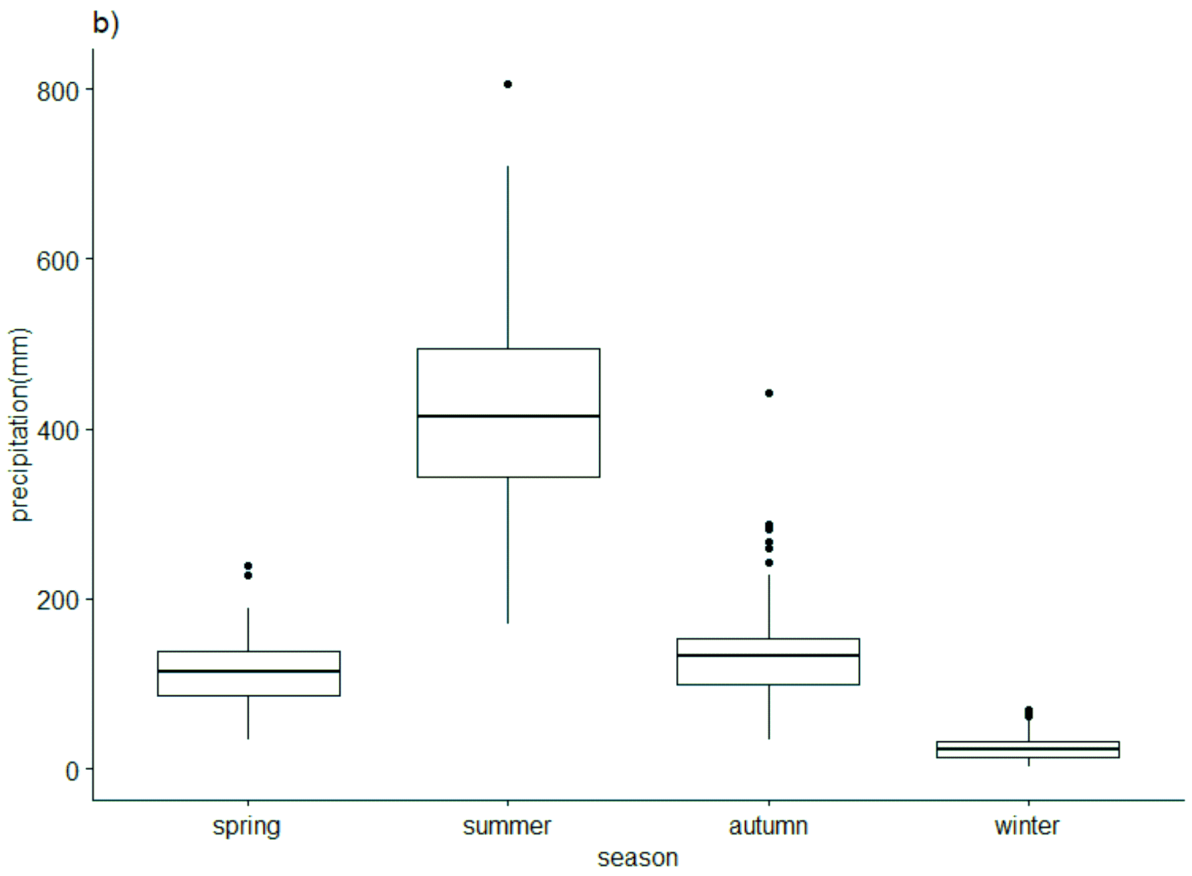
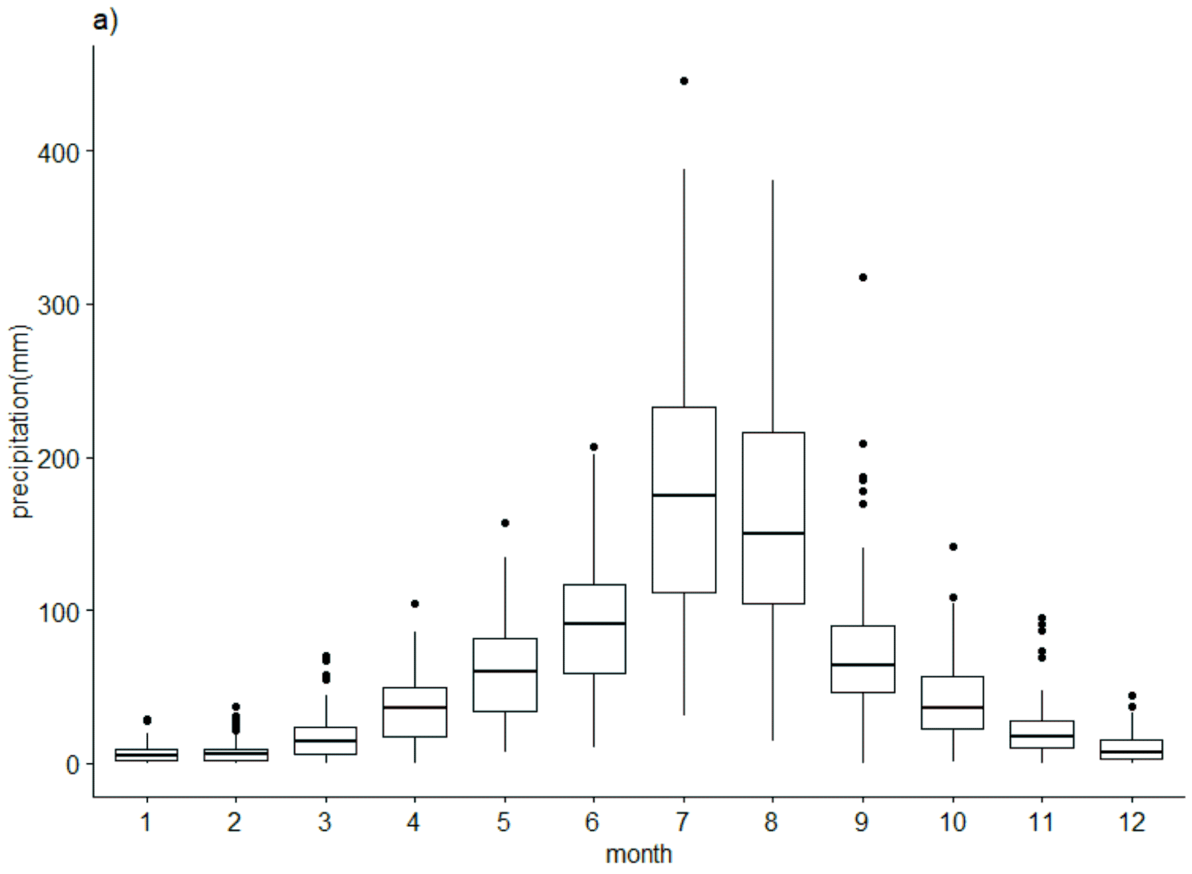
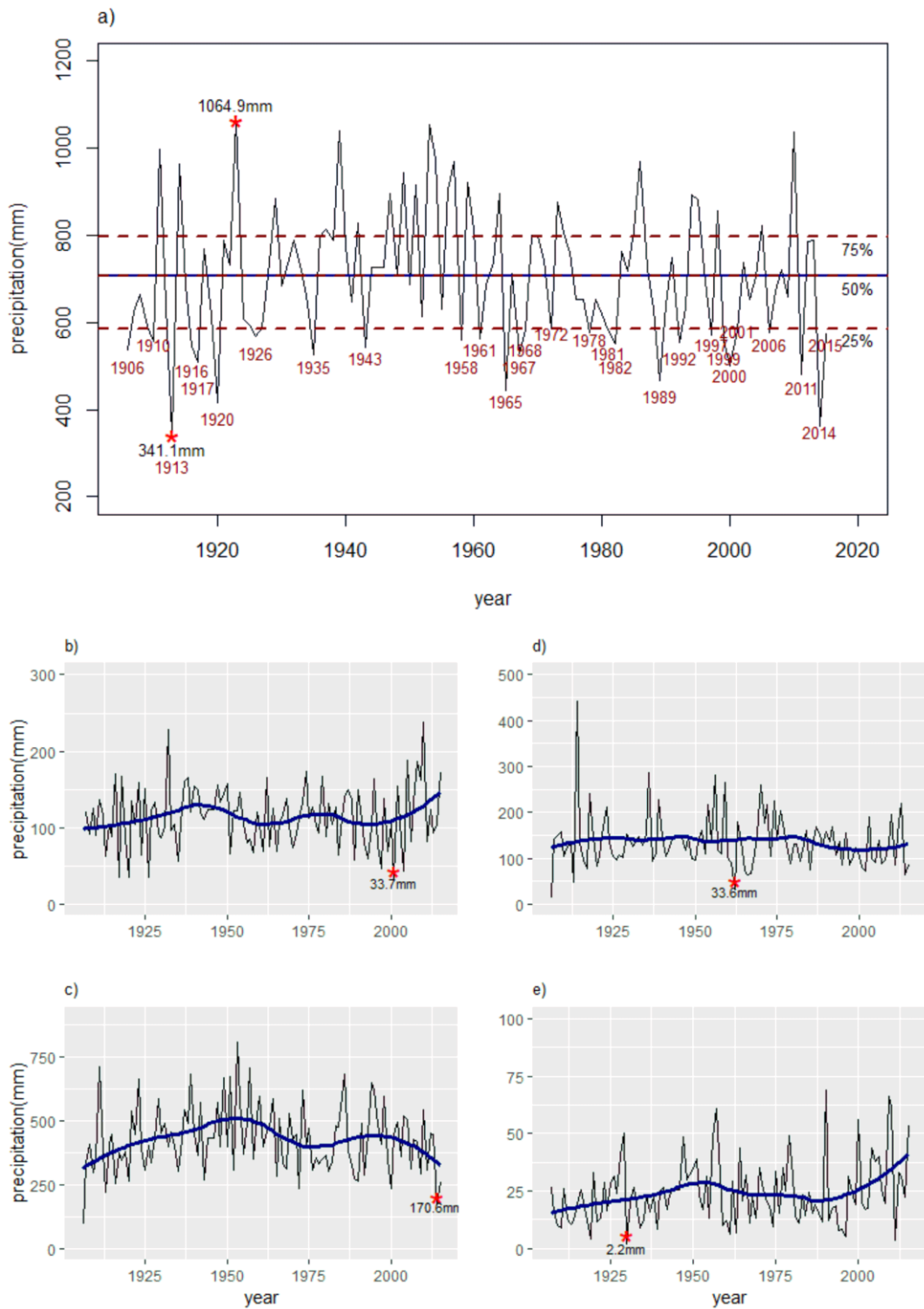


Figure 3. 1906-2015 Monthly and seasonal precipitation box chart

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

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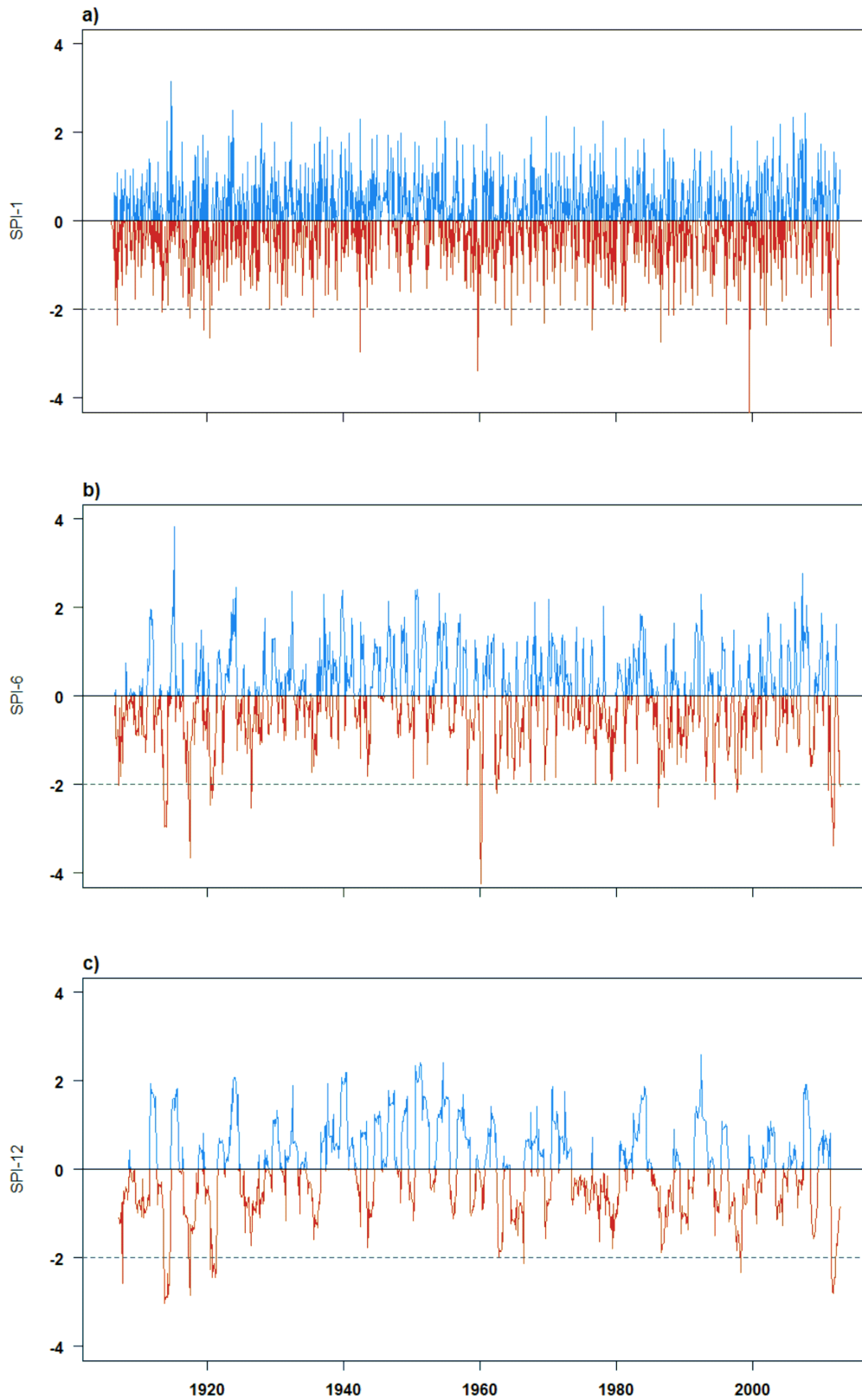
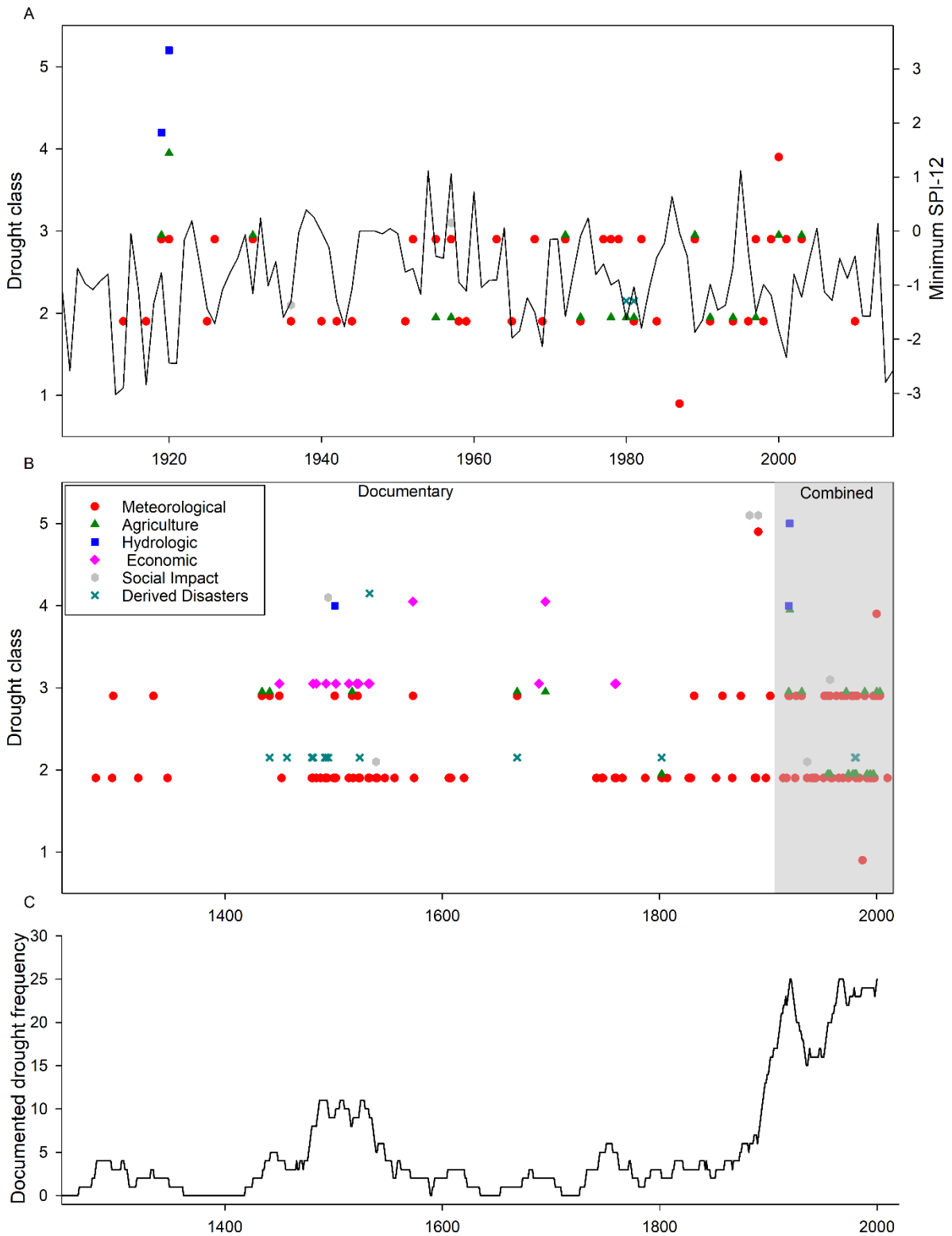


Figure 5. Standard Precipitation Index from 1906 to 2015, with wetter (blue) and drier (red) than normal conditions indicated for a): SPI-1; b) SPI-6; and, c) SPI-12

1002
1003 Figure 6. Shenyang drought classification (colour/shape) for a) combined archival and instrumental
1004 period (1906-2015) with minimum annual SPI-12; b) augmented period (1200-2015); and, c) a
1005 running 30-year mean drought frequency (1200-2015).