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

Reply to reviewer comments

Dear Editor,

Please find below a list of the reviewers comments, responses and where we have amended the text. A tracked change version of the paper is also attached along with a clean version with amendments.

We welcome all three reviewers (R1-3) for their productive and constructive comments. We are pleased to see that the reviewers recognise that this is overall a well written and interesting paper (R1-3), with relevant and appropriate methods deployed (R2), though we accept in places the clarity of the text could be improved to aid the flow of the narrative (R1 and R3). We have reviewed all the comments carefully and have stated below a response to each in turn (responses are in italics) with line numbers refer to the revised text. We felt that the reviewer's comments added value and helped improve the flow and narrative of the paper, as such we have included almost all of these in the revisions. We would like to thank all three reviewers.

Yours sincerely, LingYun, Neil, Heather, Richard and Rachel

Reviewer 1 (R1)

We welcome and thank the reviewer for their productive comments. We are pleased to see that the reviewer recognises that overall it is a well written and interesting paper, though we accept in places the clarity of the text could be improved to aid the flow of the narrative. We will carefully review all the comments that have been made and are happy to address these suggestions within the proposed revisions.

Reviewer 2 (R2)

We would like to thank the reviewer for their constructive comments and are pleased to see that they recognise that the paper is well written and interesting, with relevant and appropriate methods deployed. We are happy to address the reviewers concerns within the revisions and appreciate that these will improve the flow and narrative within paper.

Reviewer 3 (R3)

We greatly appreciate the detailed comments provided by the reviewer and are happy to address these within the revisions. It is greatly appreciated that the reviewer recognises the rigorous manner of the data analysis and approaches applied and the value of the work to the discipline.

We value the recognition of the work undertaken in the latter period, and will add further materials and analysis as requested concerning the earlier phase, however we were conscious of the recommended length in the production of the manuscript, which restricted some of the discussion (pt1). Therefore we would be happy to expand this further in adding further discussion of droughts through the period 1200-1906 (pt3), this will justify retaining the title as presently stated (pt2).

We are happy to add additional information to address and clarify the concerns relating to point 3. We note the authors concerns relating to the paper being too 'deterministic' (pt 4), we have tried to further address this and discuss throughout the paper that socio-political and cultural influences which differ over the timeframe of the study are crucial in such analysis (lines 350-359; 521-527). We have revised Figure 6 as suggested by another reviewer for the revised version of the manuscript.

Reviewer 1 (R1)

The authors present an interesting paper that reassesses long term drought and societal impacts in Shenyang, Liaoning province, Northeast China (1200-2015). My suggestions mainly concern the quality and coherence of the writing and some presentation issues. The language in the paper could be tightened significantly, which would make it easier for the reader to understand. The suggestions are not exhaustive, and I have made some other suggestions that I feel will improve the manuscript further.

We thank the reviewer for the kind comments and we will endeavour to address these aspects within the opportunity to review the paper.

General Suggestions

The placement of in text citations in certain places makes it difficult to read, suggest placing them at the end of the sentence (Lines 75-81 for example). Also, the writing could be generally improved across the manuscript. Suggest re-reading and edit the text to improve the flow of the writing in places (for example; lines 69-72 are difficult to read and could be written much clearer).

The location of references within sentences is important in clearly articulating sources for various points, we do however acknowledge that there is disciplinary variability in this practice.

Specific suggestions

Line 26: Add "common era for the reader who does not know what CE means. Or omit CE or rephrase to" the year 2000" same for line 28,33. *Accept – CE removed*

Line 49: Should not be "an" change to a. *Accept – n removed*

Line 52 Suggest changing sentence to read; "there is no universal definition for drought with a variety of definitions used around the world", with many focusing on a deficiency in precipitation over a period of time" *Accept*

Lines 56-60 Suggest re wording this paragraph, it is a bit repetitive and can be tightened up somewhat to be more concise. *Accepted*

Line 58,59 and 62 I don't like the use of e.g. too much try using "for example" or "such as". *We have retained on line 58/59 as within brackets for brevity, but modified for line 61 where it is part of the sentence.*

Line 63, 64: Define the 5 types of droughts for the reader, they may not be familiar with them. *These are listed in lines 62-64, with references to permit the reader to follow up, these are explored in further detail later within paper and we feel that at this stage it is unnecessary to detail further.*

Line 68 should be double quotes for a direct quote. “drought means various things to various people, depending on specific interest” *Accept*

Line 92 no full stop after and *Accept*

Line 99 What is meant by micro, light, mid, heavy and extreme drought? *This is a five band classification devised and applied by Zhang et al. 2008b, the classification is related to agricultural grain yield, therefore we have edited the text to help the reader see that during the period 1949-2000, 14 years were considered as either severe or extreme.*

Line 104 Is rainfall and snow depth only recorded in 1736 or from 1736? *From - clarified*

Line 109 Suggest changing “but felt acutely in China” to “but drought poses a serious threat to food security, environmental ecology, urban and rural water supply in China” *Accept*

Line 127 delete and, C2 Line 127 use million not M, same elsewhere ‘*and’ retained as correct. M changed to million*

Line 194-196 Are these station ID’s or collections? please clarify Also it is unclear whether you are using the other variables besides precipitation in your analysis of drought? If not, why present please clarify. *These are parameter codes. We only use precipitation data, however more complex analysis could use other variables- text added to explain this – line 194.*

Line 203 (1960-?) to date? *Correct - added*

Line 207 Change to “is used in this study” *Accepted*

Line 227 Belonged not belonging. *Accepted*

Line 238-271 This paragraph is difficult to follow and requires re-writing. It is unclear if you are using individual station data or a mean composite of all stations. It is also unclear which datasets you are referring to, you need to name your datasets clearly at the onset and be consistent throughout. If you have 60 sites with precipitation records why not perform some homogeneity check on them using pair wise detection? This section needs a some more work to make it much clearer and more coherent for the reader.

We have improved the clarity by clearly stating the dataset from which the data is derived. We are unable to undertake a conventional pair-wise analysis to infill as several of the data gaps are present across multiple series.

Line 290 if you have temperature records have you considered using SPEI to include ET?

This would be possible and we did consider it and it may be something we apply in other research, however the focus of this paper is in extending the record back, beyond instrumental series this would present a different focus to the paper.

Line 293 Are you using the China <.50 as drought onset or the widely used McKee and WMO classifications? It is unclear.

We use the China classification as the research was undertaken for China and ensures it is comparable to other Chinese studies.

Line 295 A useful paper to look at is Noone et al. 2017 (https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.4999) whose 250-drought analysis for Ireland identify and clearly present drought duration, severity, timing in long precipitation records and verify drought periods with documentary evidence. *Reference added*

Line 303 Why use SPI-1 and not SPI-3 for identifying agricultural drought? *We only discuss agricultural drought in relation to documentary sources*

Line 457-458 Which SPI accumulation are these values (SPI-1, 6 or 12)? Same elsewhere e.g. lines 493-499, please clarify the SPI accumulation. *Accepted, clarified*

Line 465 Change to "5000,000 people died" *Accepted*

Line 468 Change 3m to 3 million people *Accepted*

Line 473 Similar accounts of praying for rain can be found in other parts of the world see Murphy et al. 2016 (https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/wea.2904)

Line 476-482 Suggest breaking up this sentence it is very long. *We have left as is, we feel this is acceptable as a list of actions*

Line 509 Why do you think SPI has a significant correlation with ENSO3.4 summer and autumn? Give some explanation to the reader. *The accumulated SPI-12 reflects a long term deficit, which will result in the severest elements of the drought materialising in summer/autumn, therefore the correlation with summer and autumn ENSO3.4 is a reflection of a longer lagged process*.

Line 534 Could the lack of documentary evidence to support the identification of drought in the observations be issues with the data itself? Have you explored this possibility? See Murphy et al. 2019 (https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/joc.6208) *Yes, we don't think a lack of data is the issue, we think it is the changing vulnerability of populations, and the fact that the vulnerability changes considerably over this period, with the textual analysis capturing that change, therefore where once loss of life would have been common, the same magnitude drought today does not result in loss of life. We have revised the text to state this more explicitly. Line 541-545*

Figure 1 suggest filling the colour of the Liaoning province on the map of China and remove the dotted guidelines. *Revised and simplified in line with R1 request*

Figure 5 add in dotted lines at the value of onset of drought, moderate, severe, and extreme drought to plots, you will need to change the axis values.

We initially had the figure presented as suggested, however it was difficult to read and we felt looked cluttered, therefore we reduced to just demonstrating those events that are classed as 'extreme' droughts, within the paper we focus on these events, therefore we propose to retain as presented.

Figure 6 It is difficult to interpret this plot, suggest a better description in the figure caption or redo plots to make clearer. There is a lot going on in these plots and I'm not sure that they should be combined as they are for different periods. Please rethink how to display the results.

Revised and caption expanded

Reviewer 2 (R2)

Based on the instrumental data and historical documents, this study reassessed long term drought risk and societal impacts in Shenyang, China (1200-2015). A standardised precipitation index was developed to combine a long drought series. Then the series was analysed for drought frequency, severity, typology and their social impacts. The study is interesting and the methods are appropriate. My suggestions are as follows.

Thank you for the supportive and helpful comments on the paper.

General Comments:

(1)The description of the Data sources especially the instrumental data (Chapter 3.1.2) is not clear enough now. I suggest rewriting this part and making the following concerns clear.

a. the introduction of the datasets

b. which sites were used in this study and where are their locations

c. what kind of data were used from the dataset and how they were dealt with

We hope that the amendments that have been made in relation to R1 have helped address these concerns, we have also made addition amendments to support the points your raise above.

(2) The figures especially the Figure 1 and Figure 2 are not clear enough with too small numbers/words and little explanations on the lines, dots and so on. I suggest displaying the figures with a larger fonts and better legends or illustrations. *We accept and have revised*

Specific suggestions:

Line 26: delete “CE” or explain it when it comes out for the first time *Accepted*

Line 49: change “an” to “a” *Accepted*

Line 104: change “in 1736” to “from 1736 to 1911”. The records of “Yu- Xue-FenCun”(the depth of rainfall and snow) are only available in this period *Accepted*

Line 127: delete “and,” Line 227: change “belonging” to “belonged” *Reject, see comment to R1/Accepted*

Line 233-236: change another example. The example here is inappropriate. In ancient China, there were many circumstances may result in no tax. For disasters, not only droughts but also floods, earthquakes, infectious diseases and astronomical hazards may be the reasons for collecting no tax. For other situations, when the emperors would like to share their joys on having babies or show their mercies to the public, they may also sign a decree for tax free. In my perspective, the record here is certainly not definitive proof of drought.

Agree – we are demonstrating how such records were <u>excluded</u> from further analysis, we have reiterated this in revision

Line 293: change “People’s Republic of China” to “the People’s Republic of China”, same elsewhere
Line 298: a “)” is missing in this line *Modified*

Line 548: a “table” is missing before the “1” *Accept*

Table 1: the sentence of "Earlier weather phenomena can be converted into modern language descriptions through Oracle bones records" may lead to misunderstanding. Someone who is unfamiliar with Chinese history may think that before Qing Dynasty Chinese people use Oracle bones to record. *Amended to remove this potential misunderstanding*

Table 2: a. the column of "Periods/start time" may lead to misunderstanding. People may regard the years in the column as the start time of the dynasties instead of the region names *Amended*

b. how the administrative boundary changes during different dynasties should be mentioned in this table c. rethink the function of this table. If it has little relationship with subsequent analysis and summary, it could be moved to supplementary material.

We have retained the table, the nature of boundaries is not crucial to the discussion, the important aspect is that the settlement/region today known as Shenyang has changed name multiple times. We agree thought with the review and propose moving to the supplementary materials.

Table 6: a. Table 6 is not mentioned in the text part b. How does the column of "Classes 1-3" come out? Is it the summation of "class 1", "class 2" and "class 3"? Is there any mistake in the numbers of this column? *Accepted, was referenced as Table 7 in text – we have corrected this. We have also corrected the values in the top section of the column Class 1-3 as noted by the reviewer.*

Figure 1: a. the words and numbers are too small b. the Grid Lines with geographic coordinates should be added to this map c. the name of Liaoning can be added on the region of province d. the locations of data sites especially the instrumental data can be added to the map *Revised and simplified in line with R1 request, which mirrored some of these comments*

Figure 2: a. the words and numbers are too small C3 b. the meanings of the lines and dots should be explained to the readers *Revised*

Figure 4: the meanings of the lines and dashed lines should be explained to the readers *Revised*

Figure 5: the different meanings of different colors should be explained to the readers *Revised*

Reviewer 3 (R3)

This is a well written paper investigating the drought history and impacts in Shenyang, China, for the past 800 years. This is a worthwhile endeavour which has been approached in a rigorous manner; it fills gaps in our knowledge, since much work remains still to be done in this region. The paper presents an extensive part on data description, method of data processing, and drought identification/definition. However, the part on results and analysis is very short and almost exclusively focuses on the period post 1880/1900; this gives the paper the character of an introduction and seems as if the potential of the data has not been fully realized.

Specific comments:

1. As stated it is a fundamental problem of the paper that the section of results and analysis are not more comprehensive. This part is very short in relation to the room dedicated to methods, processing and identification. *We have attempted to redress this within the revision with further discussion, however we are already over the recommended paper length*

2. The title of the paper implies an analysis of droughts and their impacts from 1200 to 2015. However, the paper almost entirely focuses on the period 1906-2015. - The analysis of drought classification and trends for the period before 1906 is very short. Trends in this period are hardly explained; the high in drought frequency around 1500 is shortly addressed, but the sudden and massive increase in drought reports after c. 1880 is not contextualized. Is this skyrocking of drought frequency and severity real or due to data survival or changes in the nature of the documentary sources employed? *We do discuss the increases in the text, however we have added a little further information to this section, including to other sources who discuss droughts in China.*

If the rise in droughts is not linked primarily to data availability and nature, is there an explanation for it? - This veritable explosion in drought frequency and severity around 1880 highlights the general problem of the availability, reliability and nature of the documentary information; the problem increases in general the further back in time one goes. The authors state 'such volume [of information] limits the capacity for cross checking and validation, with many sources not easily accessible. This has raised questions of reliability and transparency, but as Bradly notes, the compendium produced by Zhang clearly illustrates critical analysis, with careful checking for consistency and discrepancies identified.' (p. 6 lines 164-168) and 'great care was undertaken in assessing the historical record' (p. 7 212). This is all rather vague and gives no indication of the measures actually taken to ensure data quality. Compilations of past weather information are notorious; older ones are marred by problems with misdating, doubling, misallocation and general misunderstandings. Zhang's compilation is younger, but the reader is not informed, how its validity was verified. Since the majority of the study period is covered by documentary data alone, this is a question of high significance.

If you consider Figure 6b you will note that the impacts of the droughts in the historical period increase in magnitude in the period c.1880, but not the frequency, therefore we do not believe that this is just a change in recording, the frequency of droughts c.1500 is greater just not as high magnitude in terms of the impact, the change in the 1880s is one of social and cultural change coupled we believe to a particularly drought rich phase as we state in the conclusion, this has been reinforced in the revisions. Where possible the archives and records have been checked and Zhang's records for significant droughts, however this is challenging for all accounts.

3. In the section on drought vulnerability, impacts and reaction are studied on the example of two 20th-century droughts. These are fine, but it would be beneficial to add a more systematic summary. Information on earlier droughts would help to complete the picture.

We have added a little further information, we discuss the droughts of 1883 and 1891 in the previous section, illustrating the first class 5 drought and examining the recorded impacts – however, the absence the rainfall/SPI information prohibits statistical comparison

4. On occasion the paper appears deterministic, as in 'Drought can be considered as the most disastrous natural hazard within China, with over 465,000 deaths and more than 3.1billion adversely affected from 1970-present and 12 million deaths since 1900' (p. 4, lines 93-95).

The above is recoded within an Internationally recognised database, in this case EMDAT, which attributes those deaths to droughts, we fully appreciate as we note in several places through the text that socio-economic and cultural factors contribute, however, within the database more deaths are attributed to drought in China than any other natural disaster. The particular character and nature of that classification is defined within the EMDAT, a UN supported database, with accountable and defined definitions. I do not think that the above statement to which the author takes exception is unreasonable as this database is used by the UNISDR.

The impact of droughts – in its most severe form famines or epidemics – is not merely due to the meteorological stressor, but is also formed by socioeconomic, political and institutional structures, which can raise or reduce vulnerability, especially the mortality rate, considerably. *Agree – see section 3.3.3 for example which details this, we also recognise and state this several times within the paper and is again repeated in the summary.*

5. P. 4 lines 98-99: 'Between BC 206 and AD 1948, 1056 severe droughts are recorded in Chinese history.' Almost half of this period is classified as 'severe drought' in this phrase, this is a very high percentage. Hence either the definition of 'severe drought' within the (diverse) Chinese climate, or the number of 'severe droughts' needs to be reconsidered. Possible shifts in the geographical extent of China over this long period of time also need to be considered. *These droughts are not affecting all parts of China, with regional variations, so most years some part is impacted by drought.*

6. P. 4 lines 101-104 mentions early Chinese precipitation records. A short explanation on these observations could be added since many readers will not be familiar with this subject (persons or institutions carrying out the observations, mention of types of instruments used if not the 'normal' rain gauges.)

We refer the reader here to the paper by Ge et al. (2005) that is cited, as we are already over the recommended word length, this would not be a simple explination as illustred by Ge et al.

7. The paper needs to go through language editing for minor orthographical and style problems.

Accept - reviewed

8. Fig. 6. This figure is somewhat confusing. Fig. 6B probably is for the whole study period 1200-2015 as is Fig.6C, but the axis of Fig. 6B is not labelled and hence the time scale is unclear. *We have added additional text to the Figure caption to clarify*

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

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

Abstract

The occurrence of two severe droughts in Northeastern China since ~~CE~~ 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 ~~CE~~ 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 ~~CE~~ 2000 occur in the instrumental series during early twentieth century (e.g. 1907, 1916-18 and 1920-21), and coeval archival sources reveal the human impacts of these severe droughts. The archival sources demonstrate how reduced vulnerability resulting from societal and cultural changes in the early twentieth century helped prevent the loss of life experienced during comparable severe droughts at the end of the nineteenth century (1887 and 1891). Incorporating a longer temporal perspective to drought analysis shows that onset is often earlier than is documented explicitly within the archives, and so combined SPI series for a region could provide an early warning of drought development expressed as a water deficit in the previous year. Analysis of archival data provides a rich historical description of impacts and societal responses to severe drought. The archives provide a rich historical description of drought impacts and responses at the personal and community level, whilst also detailing the different roles played by communities, state and international organisations in responding to events.

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

1 Introduction

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

China is one of the most natural disaster-prone countries in the world (Dai, 2011; He et al., 2011; Loorbach et al., 2011), and~~.~~ droughts are a recurrent feature of the Chinese climate (He et al., 2011). Drought can be considered as the most disastrous natural hazard within China, with over 465,000 deaths and more than 3.1 billion adversely affected from 1970-present and 12 million deaths since 1900 (EMDAT, 2019). Historically notable droughts in 1876-1878, 1928-1930 and 1958-62 resulted in widespread loss of life, poor harvest, leading to serious social consequences of famine, robbery, unrest, and political instability (De Châtel, 2014; Janku, 2018; Teklu et al., 1992; Yang et al., 2012). Between BC 206 and AD 1948, 1056 severe droughts are recorded in Chinese history, though not spatially coherent (Zhang, 2004, 2013); in the period 1949-2000, Zhang et al. (2008b) identify~~with 11 years of micro-drought, 13 years of light-drought, 14 years of mid-drought,~~ 10 years of 'heavy'~~-~~(severe) agricultural drought, and four years of 'extreme' agricultural ~~-~~drought ~~during the period 1949 to 2000 (Zhang et al., 2008b)~~. Precipitation recording in China has developed through time, with some of the most advanced recorded~~ing~~ globally during the Qing Dynasty (CE 1644-1912), with both rainfall and snow depth recorded ~~in~~from 1736 to 1911 (Ge et al., 2005). The installation of better equipment through the 1920s and 1950s saw many stations upgraded, with meteorological stations often retained; however, the availability of metadata on early recorders is more limited. Past droughts have had a far-reaching impact on society in China; a clear understanding current and future drought risk is therefore critical. With population growth, economic development, urbanisation and climatic change, drought is a global challenge, but drought poses a serious threat to food security, environmental ecology, urban and rural water supply in China ~~but felt~~

~~acutely in China, producing threats to environmental ecology, food security, impacting environmental ecology, urban and rural water supply~~ (Bohle et al., 1994; Homer-Dixon, 1994).

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

i. To develop and analyse a record of droughts and the documentary evidence for associated impacts (~~CE~~ 1200 AD - present), using a variety of sources including the compendium of Chinese droughts produced by Zhang (2004, 2013);
ii. Identify and analyse contemporary droughts using the instrumented daily precipitation series at Shenyang Meteorological Observatory (Station 54342: 1961-2015), and augment this series with the longer monthly precipitation data for Shenyang (~~CE~~ 1906-1988);
iii. Generate a Standardised Precipitation Index (SPI-1, -6 and -12) for the augmented precipitation series spanning the period ~~CE~~ 1906-2015; construct one of the longest drought series (~~CE~~ 1200 - present) combining the augmented instrumental series (ii) with historical data (i), and then classify the different types of drought and event severity; and,
iv. Analyse the patterns in drought frequency, severity and type for Shenyang, examining the documented impacts and responses to drought to better understand how societal vulnerability has changed through time.

2 Study Area

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

3 Data and Methods

3.1 Data sources

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

3.1.1 Documentary data

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

In addition to the meteorological sources identified, information from sources detailing agricultural activity provide valuable auxiliary reference materials, including the following items: Shenyang local records (Meng, 1989; Shenyang Municipal People’s Government Local Records Office (1994-2011), 2011); The year of flood and drought in Shenyang from 1276 to 1985 (Shenyang Municipal People’s Government Local Records Office, 1998). The following datasets have been acquired from the Office of State Flood Control and Drought Relief (1999);

Farmland affected area from 1949 to 1990 in Liaoning Province Statistics on Drought Area of Heavy Drought in Liaoning Province; Drought rating assessment in various regions of Liaoning Province from 1949 to 1990; Drought Statistics in the Province from 1470 to 1949; Comparison of Precipitation in Liaoning Province from 1949 to 1964 and from 1965 to 1990; Comparison of grain yield per plant, drought frequency and drought reduction in various regions of Liaoning Province; hydrological station data for Liaoning Province; Regular frequency of continuous drought in dry season in Liaoning Province. Local newspapers have also been accessed to corroborate records of droughts e.g. the Shengjing Times (reflecting the old city name).

3.1.2 Instrumental data

Instrumental climate data are taken from two datasets, the first is long-term meteorological data, including monthly precipitation (05/1905 to 12/1988) from the Research Data Archives Computational & Information Systems Lab (NCAR, 1996), no records present for 1944-1946. The precipitation records for Shenyang have also been viewed and photographed in the Chinese Meteorological Archives in Beijing. This dataset covers 60 relatively evenly distributed sites in China, with long records. The second precipitation series was retrieved from the National Disaster Reduction Centre of China (NDRCC), which provides daily data for air pressure (parameter code: V10004), daily average temperature (V12001), daily highest temperature (V12052), daily lowest temperature (V12053), precipitation (V13201), average wind speed (V11002), sunshine hours (V14032), for the period 01/01/1961 to 31/05/2016. This study uses the precipitation data (V13201), however, subsequent drought analysis could use the additional data for more complex drought modelling. Analysis of these datasets permits varying temporal analysis of the precipitation, with a long overlap period that can be used to compare the association of these two data sets.

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

3.2 Data processing

3.2.1 Documentary data

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

In the process of analysing documentary sources for Shenyang, it is necessary to pay particular attention to historical changes to the name of Shenyang and the boarders of the provinces. For example, in the book "Zhong Guo Dong Bei Yu Dong Bei Ya Gu Dai Jiao Tong Shi" (Wang and Pu, 2016), it is noted that during the Han Dynastry, 'Liao Dong Jun' was used for the Shenyang area, whereas during the Dong Han Dynasty, the southern part of Shenyang continued to belong to Liao Dong Jun, and the northern part belonged to Xuan Tu Jun (Zhao, 2006). In addition, the Gao Xian region is the recent Sujiatun area in Shenyang (Wang and Pu, 2016); Yan (2012) detailed the historical changes in the Shenyang (Table S1~~2~~).

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

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

3.2.2 Instrumental data

Data quality assessment and management of both long (NCAR) and shorter (NDRCC) series was required to ensure homogenisation and data suitability (see section 3.1.2). Total precipitation includes both liquid and equivalent frozen precipitation. All meteorological variables are recorded as one-tenth of their specific units (mm), but are converted to mm throughout. For both instrumental series, care and attention was taken with the original data series quality, with the data descriptors recorded in Table ~~3~~2. At Shenyang meteorological station, missing data occurred eight times (representing 0.826% of the record), and rainfall was marked three times with ‘R’, reflecting monthly totals identical to the previous month, raising concerns as to the validity of the data (01-02/1906, 12/1908-01/1909 and 12/1968-01/1969). There is a reduction of available meteorological data during the years 1943-46 following WWII across much of eastern China, as such no suitable local sites could be identified to infill this series; for other missing monthly data, the monthly averages are included where single months are missing, as often other local stations also have missing data. For the shorter instrumental daily precipitation series (NDRCC~~source 2~~), data descriptors are included in Table ~~3~~2, including percentage of record impacted.

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

3.3 Drought Identification

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

3.3.1 Standardized Precipitation Index (SPI)

A number of drought indices have been developed Heim (2002). Meteorological drought indicators can be divided into two categories focused on either the physical mechanisms of drought or the statistical distribution of meteorological elements; the SPI belongs to the latter group and is widely used (Lennard et al., 2015; Mckee et al., 1993). As the long precipitation series includes only monthly data, the Standardised Precipitation Index (SPI) is used, this index has a number of advantages when used over long timescales compared to other potential drought indices. The SPI developed by Mckee et al., (1993), is a widely applied meteorological drought index that quantifies precipitation deficits or excess across different climates at multiple timescales, typically of 1–24 months, however the simplicity of the SPI (precipitation as the only input) causes some limitations too, e.g. no consideration of evaporative demand (Vicente-Serrano et al., 2014). SPI values are dimensionless units, with negative values indicating drier than normal conditions and positive values wetter than normal conditions. Drought onset is generally assumed to occur at SPI values exceeding ≤1, however the National Standards of the People's Republic of China (2017) classification uses ≤0.50 as indicative of drought onset, with drought termination identified as when SPI returns to ≥0 (Table 34a); within this study we apply the classification as defined for China. SPI can be used to characterise drought duration, severity and timing of onset and termination (together known as the drought structure e.g. (Noone et al., (2017))), based on the classifications identified in Table 34a; the SPI classification recommended in China (National Standards of the People's Republic of China, 2017) differs slightly from that of the WMO (2012; Table 34 (a and c), though others have also proposed regionally specific SPI versions based on Mckee et al. (1993) e.g. Moreira et al. (2008) for Portugal. Drought duration is determined by the number of months between drought onset (SPI ≤0.49) and termination (SPI ≥0), drought severity is categorised using the SPI classification system with peak severity the minimum SPI value recorded during the drought. Within this study SPI will be examined at 3three temporal scales SPI-1 (1 month), SPI-6 (6 months), and SPI-12 (12 months) (Figure 5a-c). The SPI was determined by fitting a probability density function to selected accumulation periods using L-moments to estimate parameters. A gamma probability density distribution was found to be the most appropriate fit, using a Kolmogorov-Smirnov (K-S) test to compare empirical and theoretical fit, calculating the cumulative probability. This was then converted into the standard normal distribution, with transformation of the cumulative probability of the fitted distribution to standard normal distribution to define the SPI value (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano et al., 2010). Other univariate distributions have been recommended where a gamma distribution is not appropriate (Barker et al., 2016; Stagge et al., 2015).

3.3.2 Documentary analysis

Documentary data provides additional information beyond that offered by instrumental series, providing valuable information detailing both societal impacts and responses to past events (Pfister, 2010). At Shenyang, the first recorded drought occurs in 347 AD, but only three events are recorded during the period~~ CE~~ 347-1200, therefore the records analysed within this paper start post ~~CE ~~1200, as the frequency of records increases. Previous studies (e.g. Brázdil et al., 2009; Hanel et al., 2018; Todd et al., 2013) using historical archival sources have examined qualitative records and used a variety of different indices or grades of drought. The use of ordinal index systems for the classification of descriptive accounts in historical climatology is common, with a range of classes used e.g. Nash et al., (2016) used a +2 to -2 classification in examining wet/dry phases in Natal and Zululand in Southern Africa. In augmenting the instrumental with the historical series, clear benefits can be achieved if the descriptive classification is comparable to the SPI drought classification applied in China (Table 3~~4~~a). Therefore, five drought classes are used in considering the historical descriptions, allowing alignment between the two data forms, typical types of descriptor for each of the five classes are presented in Table ~~5~~4.

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

Annual drought values for the instrumental period (CE 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.

3.3.3 Drought trend and frequency analysis

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

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

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

4 Results and Discussion

4.1 Temporal analysis of instrumental time series

The augmented precipitation series illustrates the range of precipitation experienced at Shenyang over the last 11~~0~~0 years, with a maximum annual rainfall of 1064.9mm (1923) and a minimum of 341mm (1913). The mean of 704 mm is slightly higher than the median value (red dashed line; Figure 4a). Of the 28 years annual rainfall below the quartile, 10 occur prior to 1960 and 18 after. Precipitation at Shenyang is concentrated in the summer months, with little winter precipitation (Figure 3), typical of a continental climate. Documentary accounts often discuss spring droughts in Shenyang, which hinders the development of crops at the start of the growing season (Wang et al., 2019).

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

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

4.2 Drought classification and trends

The reconstruction of historical droughts in Shenyang is divided into two parts. The first obtains drought class information from the SPI for the period ~~CE~~ 1906-2015 from an augmented instrumental series. The second uses historical documents and is defined based on specific classification criteria shown in Table 2~~3~~ producing a long drought reconstruction from 1200 AD to 2015, with documentary (coloured) and instrumental data (black) for Shenyang (Figure 6b). Analysis of the period 1906-2015 demonstrates a non-statistically significant correlation exists in the relationship between annual minimum SPI-12 and documentary drought class for any given year, of the 107 years of record, 42 record both an SPI and descriptive account of drought. The relative absence of class 1 events in the documentary record suggests that no account is often made during ‘normal’ conditions, with absence of record often likely reflecting no drought, therefore the analysis was repeated, years with no description were attributed to class 1, as a result a statistically significant relationship is identified (Spearman, $p<0.05$).

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

tThis drought period is coeval with a previously identified reduced monsoon phase in Central China (Zhang et al., 2008a) and the Spörer period (CE 1460-1550) of reduced solar activity, this which coincides with a cold phase in China as noted by (Zhang et al., 2018a). Zhu. a 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)[-1] and parts of north Amercia (Cook et al., 2014), suggesting that this drought may have extended across more of the northern hemisphere than previous identified.

A relative quiescent phase is then noted between CE 1600-1750, with few droughts recorded (Figure 6b). A number of droughts occurring in the period CE 1750-1880 AD are documented; however, the frequency and severity of droughts increases thereafter (Figure 6c). The first drought year with an assessment of class 5 occurs in March 1883, with the Shenyang chronicles referring to drought, a cholera epidemic, and more than 20,000 deaths in a week (Shenyang Municipal People's Government Local Records Editing Office, 1989). This was followed by a second event in 1891, with documentary sources detailing famine and over 20,000 estimated deaths (Wen et al., 2005). Table 75 summarizes the frequency of droughts at Shenyang in each century, with a small peak in Shenyang drought frequency from CE 1501-1600, drought frequency then decreased until the nineteenth century (Figure 6c).

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

The types of drought recorded within the records are indicated in Figure 6b, these illustrate that the majority of records document meteorological drought conditions, followed by economic impacts. The drought severity in the descriptive accounts' places most of documented droughts in class 2 and~~,~~ 3~~ or 4~~ (Figure 6b). The absence of deaths being documented restricts the number of class 5 socio-drought, although the drought of 1920-21 is documented as a class 5 hydrological drought, the only documentary class 5 event in the twentieth century. It may be that such information was not published, and/or that the droughts within the Liaoning province did not lead to such impacts, as few events prior to the late nineteenth century approach class 5. In focussing on the city of Shenyang, there is also a risk that the impacts differed within the city to those experienced in rural communities within the province, thereby reducing the number of agricultural droughts documented. Future works should therefore focus at the provincial scale to incorporate a wider diversity of impact.

4.3 Societal vulnerability to droughts

The transformation of responses in Shenyang from *pre-industrial* (*folk*), to *industrial* (*technological*) and subsequently *post-industrial* (Chester et al., 2012; White, 1974) during the period of study presents challenges in assessing and comparing impacts. Recent droughts of comparable meteorological severity, e.g. 2014 (SPI-12: -2.8) to those of the early twentieth century, namely 190~~6~~7 (-2.6), 1917 (-2.8) or 1921 (-2.5) illustrate how the responses and resulting impacts potentially differed. In analysing these events the consequences of the droughts differed considerably, whilst these events do not record deaths among the population in Shenyang and/or Liaoning province they are severe, with the 1920-21 drought described as "Spring drought for several months, well and river dry up, land dry up, no harvest at all, winter disaster victims everywhere, people live in hunger and cold move out from the mountain village, village empty" [class 4 socio-drought but class 5-hydrological] (Office of State Flood Control and Drought Relief, 1999, p.388), across China an estimated 500,000 people died (Edwards, 1922). Analysis of the international media at the time reporting on the event is shaped by the socio-political circumstances, with The Times (London) recording 3 million~~M~~ as being displaced (9 Nov. 1920 p.11); however, as Fuller (2011) importantly notes this is often viewed from an international perspective, with local relief providers often failing to receive recognition. The responses to the drought varied, but included those expected within an *industrial* framework, with both national and international relief occurring, but also local support complimenting *pre-industrial* responses, with the Shengjing Times (1920) reporting on the 1st

July that “Chief Zhang set up an alter begging for rain” (6080, p.4). However, as Li (2007) notes in north China, population increases without apparent agricultural intensification or expansion during the late nineteenth century may have contributed to an increased susceptibility to drought associate harvest fluctuations. In comparison during the 2014 drought which resulted in a Level III emergency response, itself a notable difference from 1920 as a plan was in place, a number of responses were deployed to mitigate the impacts of the drought, these included: the provision of central and provincial relief funds (see section 4.1); water transfer of 400,000,000 M m^3 from the Hun River, securing domestic and agricultural provisions (Sun, 2015); and the provision of relief service teams to support local infrastructure improvements e.g. drilling new wells and supply or water to over 32,000 people suffering shortages (Wang, 2014). The impacts of the drought were widely reported in the media, with notably commentary focused on the impacts to water supplies and food production: “Food production in Liaoning… estimated to decline by 5 billion kg this year” (China Daily, 2014). Whilst both events 1920-21 and 2014 were severe droughts, the relief planning and coordinated effort coupled with improved infrastructure and a more stable socio-political environment facilitated a more efficient response.

4.4 Contemporary droughts and generating mechanisms

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

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

5 Summary

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

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

Data availability

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

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Ming Shi Zong Shi Lu, Vol. 353

Ming Shi Zong, Vol. 3, 7:8

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~~ier~~ accounts of weather phenomena ~~can be converted into~~ are included in accounts recorded ~~modern language descriptions through~~ in the Oracle bones records.	(Zhang, 2004)	Meteorological Records of the Last 3,000 Years
308AD - 2000AD	Liaoning	The drought chapter of this book provides a description of the drought in Liaoning Province from 308 to 2000 AD. And from 352 to 2000 AD, there were descriptions of insect disasters, famine, epidemic diseases, and some unexplained disasters.	(Li and Meng, 2005)	China Meteorological Disasters Ceremony (Liaoning volume)
352AD - 1948AD	Liaoning	Based on historical data, drought descriptions and statistics were provided for the Liaoning area from 352 to 1948. For the 12 key cities in Liaoning Province (including Shenyang), the drought rating was listed by year. This drought level assessment was based on the reduction rate of grain yield. And a statistical table of light drought years and heavy drought years for several rivers in Liaoning area is provided.	(Office of State Flood Control and Drought Relief, 1999)	Liaoning Flood and Drought Disaster
1949 - 2000	China	It provides the annual and seasonal changes of agricultural drought, the change of disaster areas, the degree of drought risk, and the measures of drought prevention and mitigation against agriculture after 1949.	(Zhang, 2008)	China Historical Drought from 1949 to 2000
2000	Liaoning	This book provides the causes, characteristics and the degree of drought and the statistics of surface water resources in each region. The degree of drought in Liaoning Province in 2000 was respectively analysed by precipitation, river runoff, crop yield reduction and farmland drought rate, and comprehensive indicators.	(Pu, 2001)	Extraordinary drought in Liaoning Province during 2000
2001	Liaoning	Data and description of drought causes, precipitation distribution, and the multi-year comparison of the net flow of rivers are provided. The drought level is determined by the extent of agricultural disasters, meteorological factors, precipitation frequency, and water supply and demand balance.	(Wang, 2002)	Spring Drought Report of Liaoning Province in 2001
1986-2005	Shenyang	This multi-year Shenyang chronicle provided the major events that occurred in Shenyang from 1986 to 2005, including some meteorological disasters. The natural environment section records the climate, rainfall, and natural disasters during the period.	(Zou, 2010)	Shenyang chronicles 1986-2005, volume one
1994-2011	Shenyang	The annual Shenyang chronicle records the climatic conditions, meteorological disasters, and some water conservation measures of the year.	(Shenyang Municipal People's Government Local Records Office (1994-2011), 2011)	Shenyang chronicles 1994-2011 (separate volumes)
1276-1985	Shenyang	In integrate Shenyang chronicle, there are statistics on flood and drought in suburbs region, Xinmin region and Liaozhong region in Shenyang city from 1276-1985.	(Shenyang Municipal People's Government Local Records Office, 1998)	Shenyang chronicle, volume eight

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

Table 2. Shenyang historical place names

Periods /start time	Region Name	References
Western Han Dynasty (140BC)	Gao Xian, Hou Cheng	(Yan, 2012)
Eastern Han Dynasty (108AD)	Liao Dong Jun, Xuan Tu Jun	(Lu and Teng, 2000; Yan, 2012)
Three Kingdoms Period (238AD)	Xuan Tu Ju, Gao Xian	(Yan, 2012)
Jin Dynasty (404AD)	Gai Mou Cheng	(Yan, 2012)
Tang Dynasty (670AD)	Gai Mou Zhou	(Yan, 2012)
Five Dynasties and Ten Kingdoms Period (916AD)	Shen Zhou	(Ge, 2005; Yan, 2012)
Yuan Dynasty(1296AD)	Shen Yang Lu	(Yan, 2012)
Northern Yuan Dynasty (1386AD)	Shen Yang Zhong Wei	(Yan, 2012)
		(Yan, 2012)
Ming Dynasty (1634AD)	Shengjing or Sheng Jing	(Yan, 2012)
Qing Dynasty (1657AD)	Feng Tian	(Yan, 2012)
Qing Dynasty (1664AD)	Cheng De Xian	(Yan, 2012)
Republic of China (1929AD)	Shen Yang Shi	(Yan, 2012)

Table 23. Data Information Description Table

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

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

Table 34. SPI drought classifications applied within different regions, a) China Grades of meteorological drought (National Standards of the People's Republic of China, 2017); b) the arbitrary drought intensity classes originally defined by Mckee et al. (1993); and, c) as used by the WMO (World Meteorological Organization (WMO), 2012).

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

Table 45. Drought class and phenomenon comparison table

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

Table ~~6~~5. The frequency of droughts in Shenyang since 1200 AD and associated drought class (see Table 4~~5~~). 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	~~2~~4	0
1301-1400	2.3	3	0	2	1	0	0	3~~2~~	0
1401-1500	2.6	14	0	7	6	1	0	~~7~~13	1
1501-1600	2.6	17	0	9	5	3	0	14~~9~~	3
1601-1700	2.5	6	0	3	3	0	0	~~3~~6	0
1701-1800	2.1	7	0	6	1	0	0	7~~6~~	0
1801-1900	3.1	12	0	9	3	0	2	~~9~~12	2
1901-2000	2.4	74	23	16	21	9	5	60	14
2001-2015	2.9	14	2	4	3	3	2	9	5

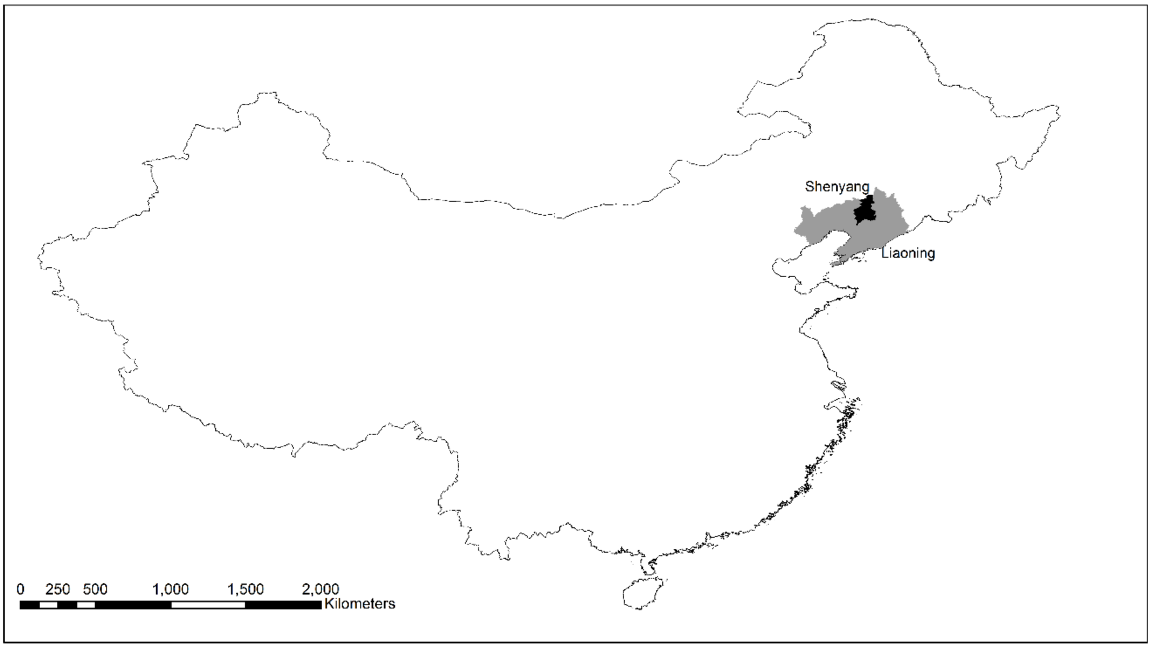
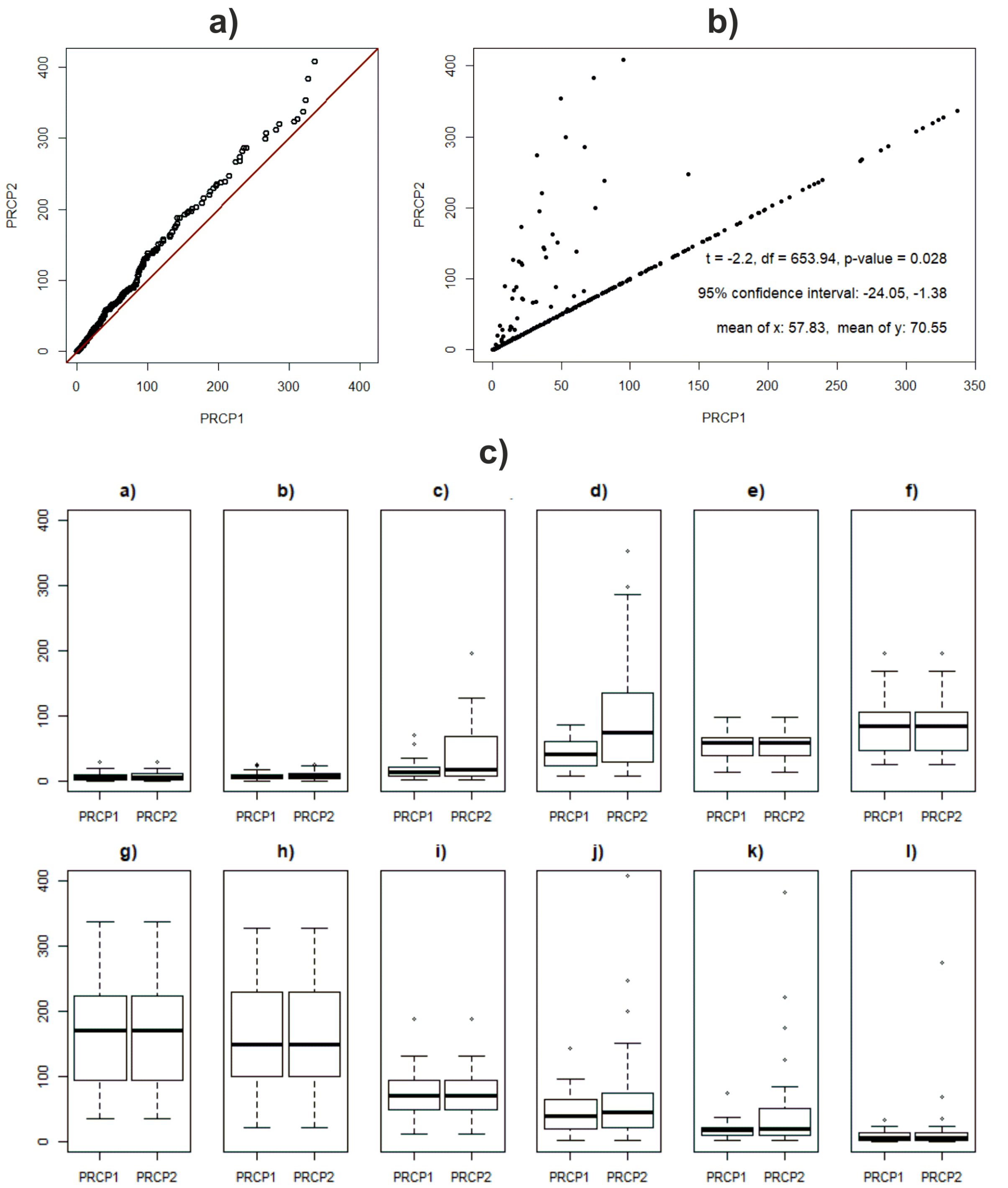


Figure 1. The geographical location of Shenyang, ~~in~~ Liaoning province and China



a)
b)
PRCP1
PRCP2
t = -2.2, df = 653.94, p-value = 0.028
95% confidence interval: -24.05, -1.38
mean of x: 57.83, mean of y: 70.55
c)
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)

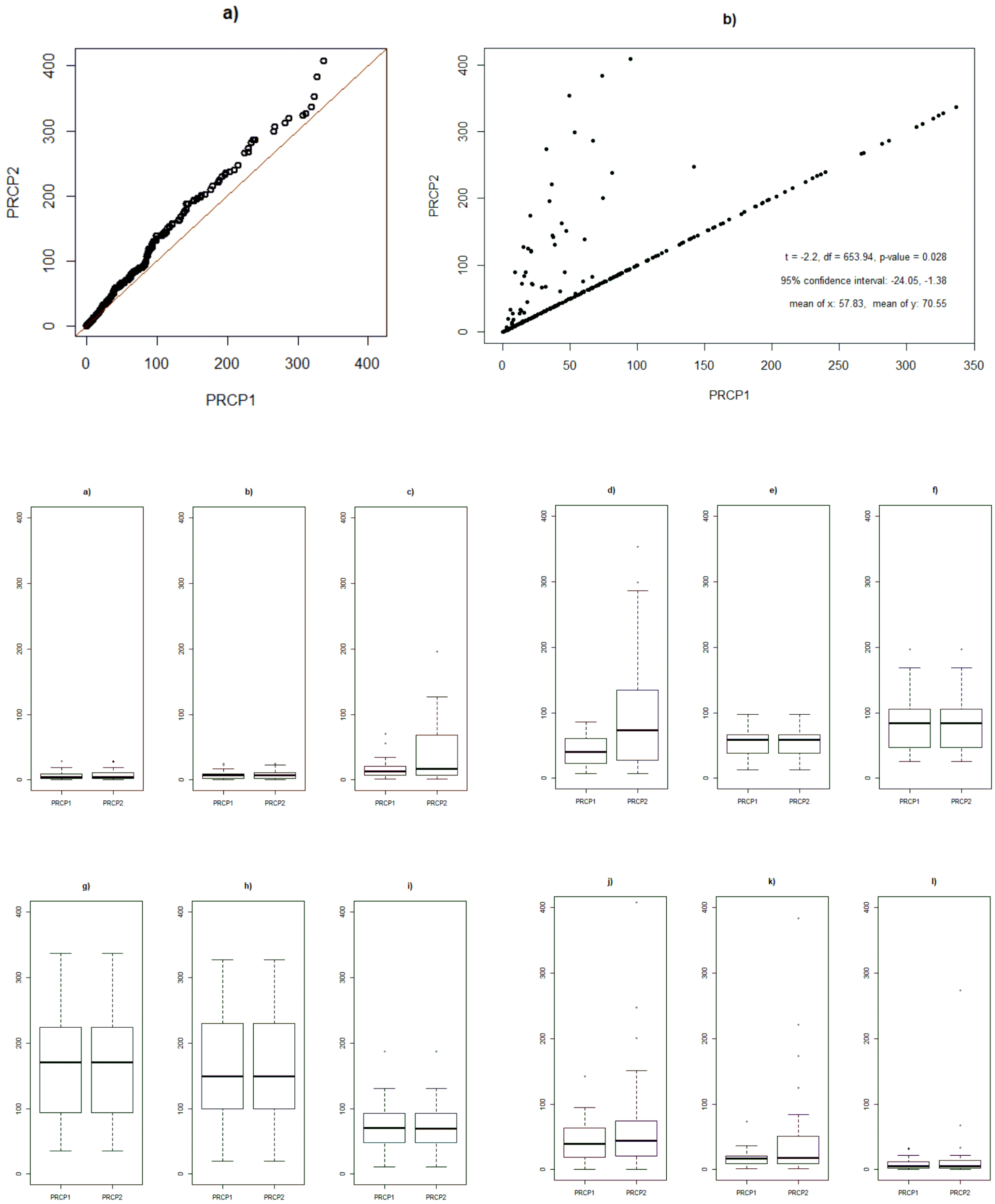


Figure 2. a) QQ plot of two precipitation (mm) data sources (p-value 0.028); b) monthly precipitation comparison of two datasets (significance Analysis of Precipitation from 1961 to 1988); c) monthly precipitation distribution and outliers (a-l: January to December)

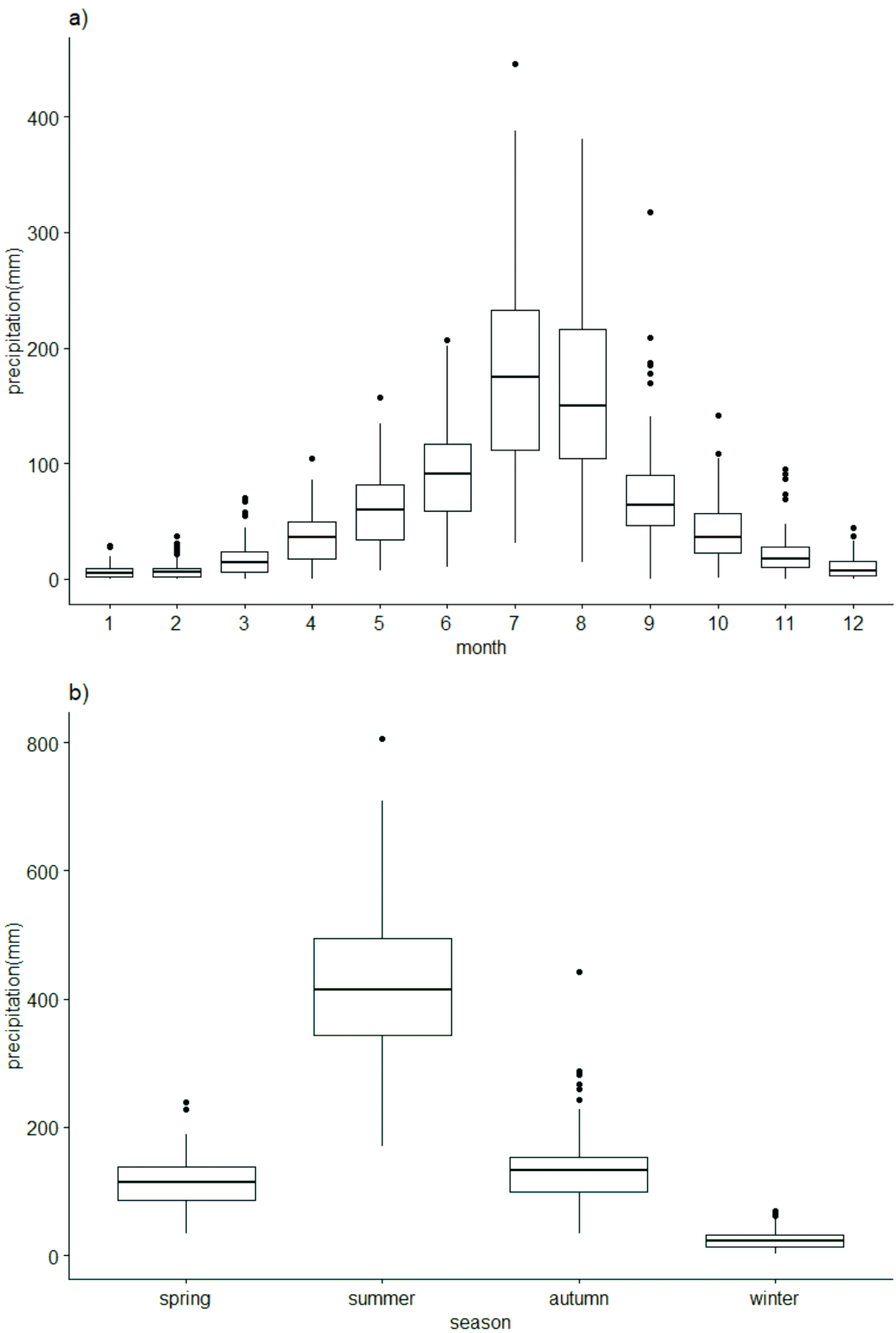


Figure 3. 1906-2015 Monthly and seasonal precipitation box chart

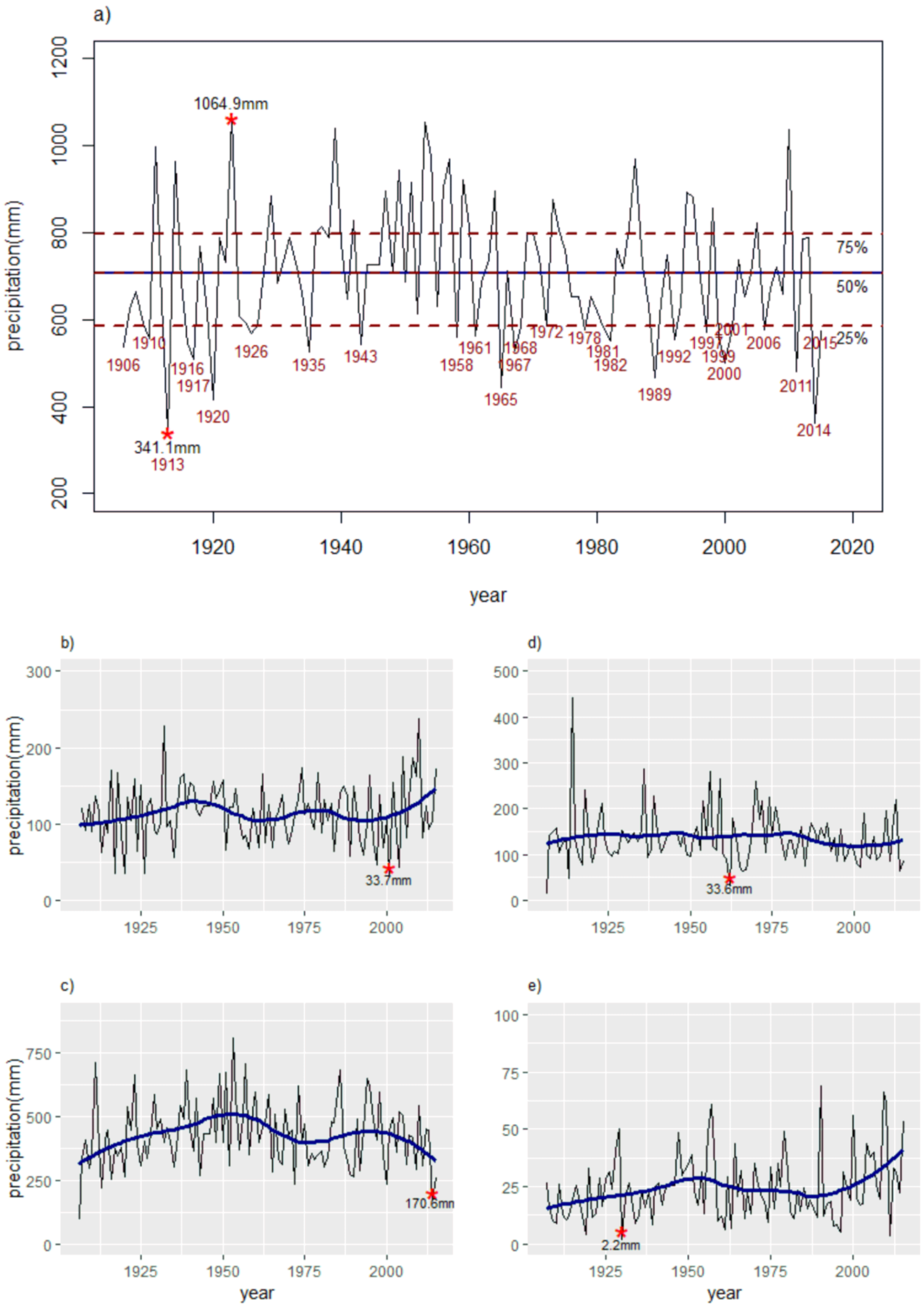


Figure 4. Annual and seasonal precipitation from 1906 to 2015, a) annual (quartiles indicated by dashed lines); b) spring; c) summer; d) autumn; and, e) winter. A 30-year Savitzky-Golay filter is presented (bold line b-e).

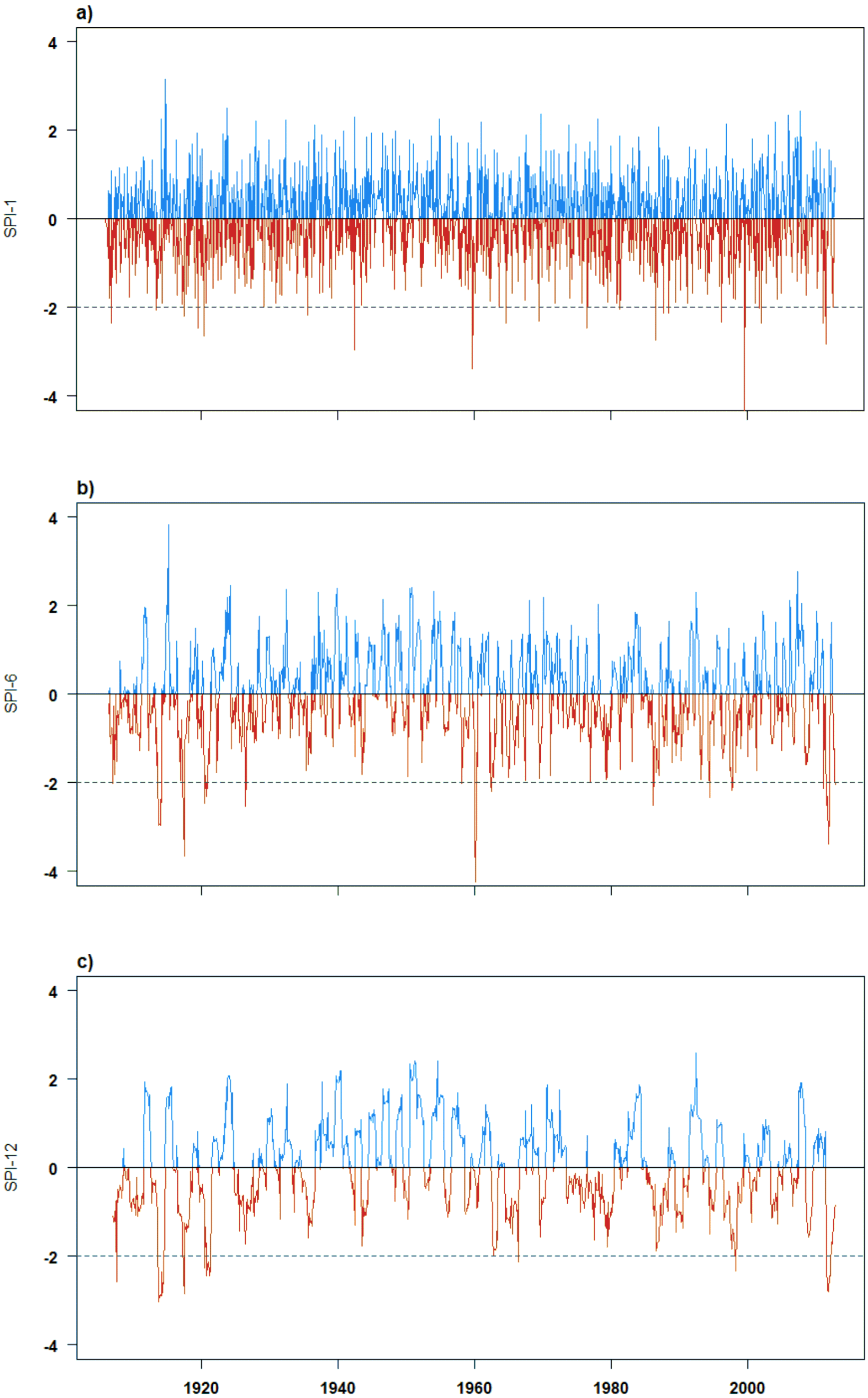
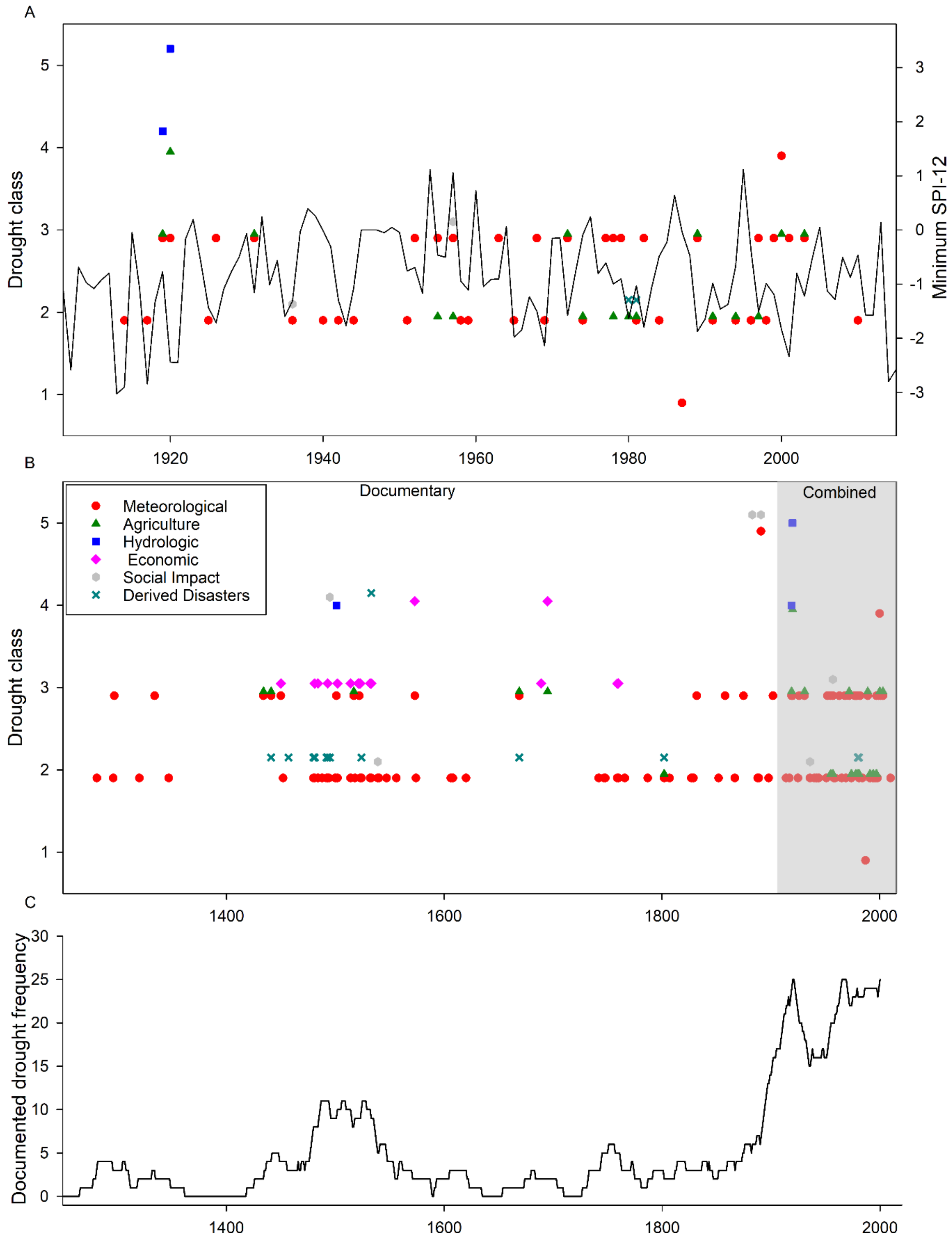


Figure 5. Standard Precipitation Index from 1906 to 2015, with wetter (blue) and drier (red) than normal conditions indicated for a): SPI-1; b) SPI-6; and, c) SPI-12


A
Drought class
Minimum SPI-12
B
Documentary
Combined
Meteorological
Agriculture
Hydrologic
Economic
Social Impact
Derived Disasters
C
Documented drought frequency

989

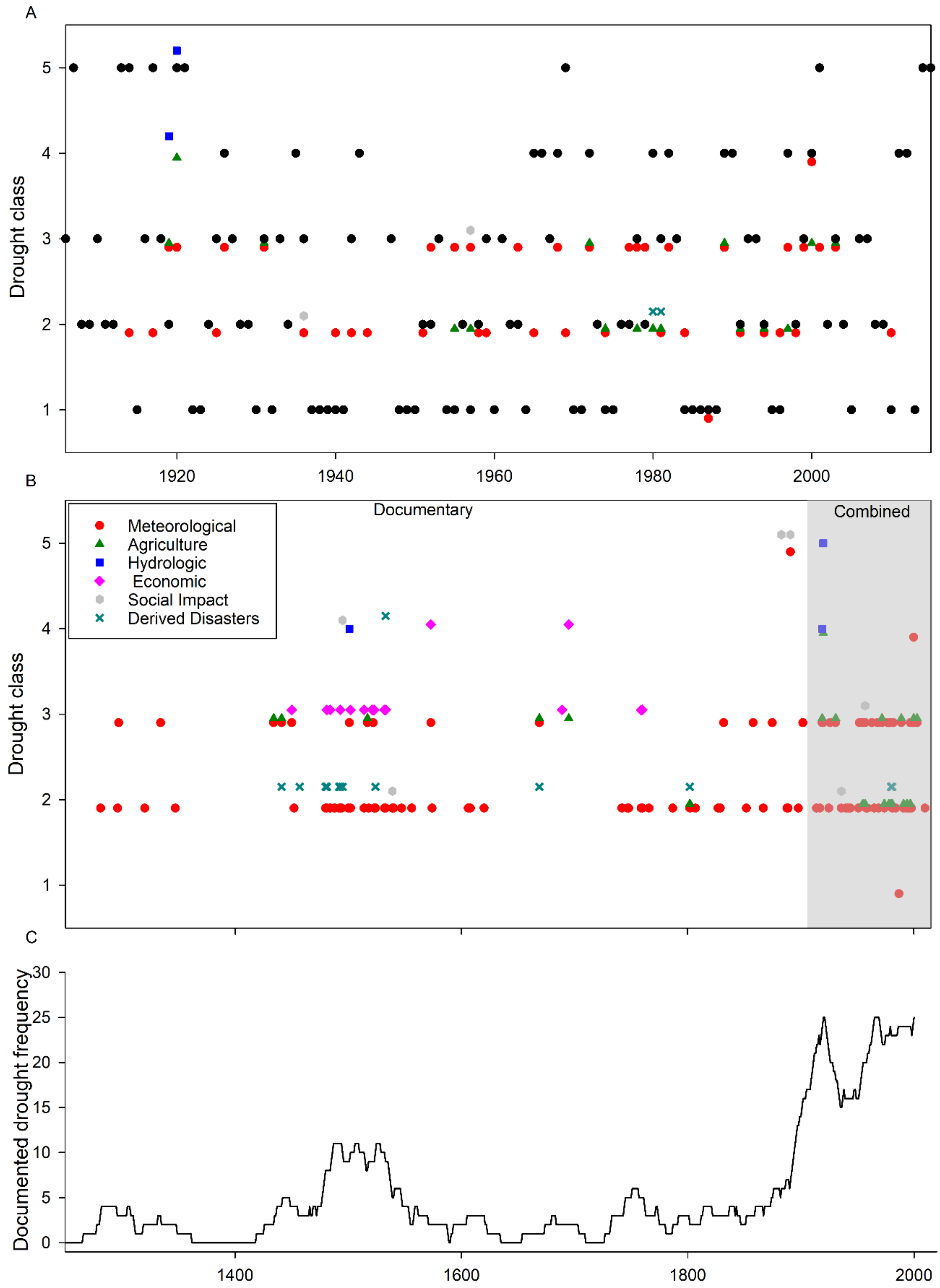


Figure 6. Shenyang drought classification (colour/shape) ~~with instrumental (black) and documentary sources (colour/shaped)~~ for a) combined archival and instrumental period (1906-~~present~~2015) with minimum annual SPI-12; b) augmented period (1200-2015); and, c) a running 30-year mean drought frequency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

Table S1. Shenyang historical place names

Dynasty (start of name use)	Region Name	References
Western Han Dynasty (140BC)	Gao Xian, Hou Cheng	(Yan, 2012)
Eastern Han Dynasty (108AD)	Liao Dong Jun, Xuan Tu Jun	(Lu and Teng, 2000; Yan, 2012)
Three Kingdoms Period (238AD)	Xuan Tu Ju, Gao Xian	(Yan, 2012)
Jin Dynasty (404AD)	Gai Mou Cheng	(Yan, 2012)
Tang Dynasty (670AD)	Gai Mou Zhou	(Yan, 2012)
Five Dynasties and Ten Kingdoms Period (916AD)	Shen Zhou	(Ge, 2005; Yan, 2012)
Yuan Dynasty(1296AD)	Shen Yang Lu	(Yan, 2012)
Northern Yuan Dynasty (1386AD)	Shen Yang Zhong Wei	(Yan, 2012) (Yan, 2012)
Ming Dynasty (1634AD)	Shengjing or Sheng Jing	(Yan, 2012)
Qing Dynasty (1657AD)	Feng Tian	(Yan, 2012)
Qing Dynasty (1664AD)	Cheng De Xian	(Yan, 2012)
Republic of China (1929AD)	Shen Yang Shi	(Yan, 2012)

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

Reply to reviewer comments

We thank this fourth separate reviewer for the insightful comments and suggestions on the paper, which we provide detailed responses to below. We have enacted the majority of these, however for a few we felt there was good reason not to expand/develop or modify the text as suggested. We hope that the editor and reviewer are happy with our justifications and modifications made here and to the previous reviewers. Our responses are provided in italics below.

Responses to reviewer #4

Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)

1. The manuscript presents a data-driven study, meaning the authors should be more careful about the data quality. The authors checked the data homogenization between NCAR dataset and station observations in manuscript. However, station NO. 54342 **relocated** many times**, i.e. the year of 1970, 1976, 1989, 2006,** etc. A study mentioned (Li et al, 2014. Title: Effect of data homogenization on estimate of temperature trend and urban bias in Shenyang station; The abstract in English) relocations could affect record (i.e. temperature) due to the non-uniformity during observations. Therefore, it will be good to check: Whether and how does the relocations affect the precipitation?

We thank the reviewer for drawing attention to this, we undertook this analysis originally but excluded from the paper, so we have inserted the homogenisation testing that we did, with a comment inserted on Line 257:

"The precipitation record for Shenyang has four station relocation's/instrument renewals during its monitoring record (October 1970, October 1976, January 1989 and June 2006). An analysis of the homogeneity of the record was undertaken using the approach presented by Li et al. (2014), when assessing temperature changes in Shenyang. A correlation analysis of Shenyang with the nearby Benxi precipitation station record (~41 km southeast of Shenyang) demonstrates a stable difference (prediction ration) between the two series for all periods and an R^2 throughout of >0.88 (Table S2). In the absence of any evident changes within the precipitation record resulting from localised station relocation/instrument renewal we consider the precipitation data at Shenyang to be homogeneous and reliable."

We have also include a supplementary table (S2) demonstrating this

Table S2. Influence of relocated in Shenyang on precipitation data

Periods between station location changes	Shenyang (mm)	Benxi (mm)	Rainfall ratio	Relative change	R^2
1955 JAN - 1970 SEP	60.61	67.75	0.89	0.118	0.89
1970 OCT - 1976 SEP	60.72	68.38	0.89	0.126	0.90
1976 OCT - 1988 DEC	57.14	64.28	0.89	0.125	0.88
1989 JAN - 2006 MAY	55.78	62.89	0.89	0.127	0.87
2006 JUN - 2012 DEC	60.87	72.16	0.84	0.185	0.88

2. Could you discuss the reason to use SPI-12 instead of SPI-6 more specific?

Re: Line 357: We opted to use the SPI-12 in preference to SPI-6 (or shorter timescales), as precipitation in Shenyang has such a strong seasonal skew toward the summer months, use of SPI-12 also permits a stronger analysis of interannual drought, a key feature in this paper over the long-period analysed.

3. The long-term drought series and documentary records from C.E. 1200 was a very interesting point of this study. This study period covers at least three types of government in China, including empire era, warlord era, and the current stage. Could you discuss the difference on societal impacts when a same/similar level of drought occurred during the different era/period, in particular for the pre-instrumental observation period? If possible, a further question, what's the difference on societal response when a same or similar level of drought occurred during the different period? Such as the leading group, government or local group/companies; the supporting funding, etc.

This is an interesting point and we do discuss this briefly in section 4.3, however a detailed but concise discussion of this is not possible within the paper, though we acknowledge that it is an interesting and challenging point, such a discussion would require unpacking a number of socio-political aspects. We plan to explore this further within a subsequent paper for Beijing in which we have reconstructed a long monthly instrumental precipitation series back to 1724, with extensive historical records, we feel that this type of analysis is better suited to the Beijing study.

4. Is **ENSO** the best natural driving factors for drought in Shenyang? Did you consider about sunspots, temperature/heatwave, or volcano eruptions (normally have signal in extreme climatic events)?

In exploring long-term drought in Shenyang we considered the role of ENSO as several previous studies, using shorter series as noted in the paper, identify a relationship between drought and ENSO. Whilst we undertook a brief analysis of the relationship between volcanic events and droughts, no clear discernible relationship was identified. It is difficult using historical records to differentiate between

drought/temperature/heatwave, with these phrases and terms often interchangeably used to define the events. The influence of sunspots, or a proxy solar energy signal is something we are currently exploring further.

5. ENSO effect precipitation was not a point to point impact (i.e. Wang et al, 2000; https://doi.org/10.1175/1520-0442(2000)013<1517:PEATHD>2.0.CO;2). Each step need energy and time cost, thus, it may cause you hard to get high confidence on correlation if you use the ENSO series and droughts in the same season. Did you try correlated the pre-season ENSO to drought series (the level data, therefore your historical data could be included)? Such as spring drought to autumn/winter ENSO, summer drought to spring ENSO, etc.

The use of SPI-12 actually helps address this issue, as in using the SPI-12 and lag or delay in the signal from the ENSO to precipitation should hopefully be captured, this is particularly true in Shenyang where the majority of the precipitation falls in the summer months, we also considered longer SPI- series timescales, however these failed to determine any further relationships. We do though recognise that there is a risk in using a longer SPI that some dilution of signal may occur.

6. A brief comment on one of your results mentioned in manuscript many times (just a view sharing, you do not need add or explain this in detail in your work): It make sense of documentary records did not have pre-drought information, and the drought records normally started from spring. The dominant economic sector in historical China was agriculture, which is normally start from spring in north/northeast China. Therefore, personal diaries and govern documents record 'extreme/abnormal/disaster events' more than 'common records'.

We agree, irrespective of location (co-authors have extensive experience of historical droughts in Europe), the recording of conditions of drought are difficult to analyse and the nature of the impact actually is a good indicator as to the point 'within a drought' that it starts to get recorded, as the impacts of drought are felt at different stages relative to the drought type, so a meteorological drought is often noted first, with a groundwater drought much later, with other droughts, hydrological, agricultural, socioeconomic in-between.

Minor comments

1. line 63 remove the comma between author name and the following sentence, 'Wilhite and Glantz (1985), classified droughts'. Remove the dot between 'and' and 'drought' in line 90.

Accepted. We are unable to find the issue on line 90

2. Why you emphasis the ground water drought in line 64 to 65? And what the difference between the ground water drought and hydrological drought? According to the definition from USGS (https://water.usgs.gov/ogw/drought/), ground water drought is a type belonging to the hydrological drought. And in this study, you did not separate them into two types when classify drought types (line 334).

We make the comment here simply to recognise that for some studies have separated groundwater droughts for hydrological droughts, this however is not a particularly important issue for Shenyang, but is for some areas of China and globally, with the two treated independently. Here in the UK they are now viewed separately.

3. Line 75-76: the author list many events there. Two minor comments: a. add the season instead of year only, i.e. the spring and summer of 1975 and 1976 in Europe; b. add the special name of those events, just like you did for the USA event.

We have not enacted this suggestion, as whilst the greatest impact may be felt in a particular season, the drought itself may span multiple seasons/year(s). Only one of these droughts is named as far as we are aware, that of the 'Dust Bowl' drought, which is internationally recognised and therefore appropriate in this instance we feel.

4. Line 75 and line 80: check the reference published year: Zaidman et al. According to the paper name from your reference below, this paper published in 2002 (https://www.hydrol-earth-syst-sci.net/6/733/2002/), not the year of 2010.

Accepted, this should be 2002.

5. Line 100, I would suggest to keep number in the same format: 'four years' into '4 years'.

Accepted.

6. Line 116, 'a record of droughts' into 'the record of droughts'

Accepted.

7. Please pay attention to the abbreviations you used, they may confused your readers. i.e. Line 137, 8'M' to 8 million; Capital 'M' also appear in line 395 and line 396. If you wish to abbreviate the million into 'M', please define it at the first place it shown. Line 248 'WWII' to the Second World War.

Accepted.

8. Line 170, you may need show the full name of 'REACHES' (Reconstructed East Asian Climate Historical Encoded Series) to your readers, which could help them understand the data type you used.

Accepted.

9. Line 186: you can directly write 'Shenyang was called Shengjing' in the brackets after Shengjing Times.

Accepted. We have also linked to Table S1.

10. Line 192: just need a quick check, are those NCAR data were gridded data or real station data? As you mentioned 'This dataset covers 60 relatively evenly distributed sites in China', which is, somehow, quite counter-intuitive. China has 60 stations with long term data series, but distribution were not 'evenly', at least east more than west; and from the link you attached this dataset was describe itself as 'Temporal/Geographical Coverage (each dot represents a 3° box containing one or more observations)', I'm not sure whether your 'evenly distribution' result from this. You need to check it, as gridded data with a spatial resolution of 3° x 3° (~300 km x 300 km) won't be a good choice for a city-scale study.

We have removed this sentence as unnecessary and clearly caused some confusion. All data used is observed 'real' station data.

11. Line 217 & 218 Could you put the period of the Han dynasty and Dong Han Dynasty?

Accept, The beginning year of the dynasty and the name change of Shenyang are listed in Table S1 with details. We have added a reference to the Table here.

12. Line 442: please give a percentage or number instead of the phrase 'most of'.

Accepted, we have clarified and inserted (66%) after most.

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

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

Abstract

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

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

1 Introduction

Drought is a world-wide problem, causing more deaths globally than any other natural disaster (Delbiso et al., 2017); with over 485,000 deaths and more than 1.6 billion people adversely affected during the last decade (2010-2019; EM-DAT, 2019). Drought is often a slow developing pervasive environmental disaster that is hard to predict and manage, and a variety of definitions for drought in operational use around the world, there is no universal definition for drought with a variety of definitions used around the world, with many focusing on a deficiency in precipitation over a period of time (Belal et al., 2014; Lloyd-Hughes, 2014; Wilhite, 2000). Droughts are a long-term water deficit, that often develops slowly under natural conditions or through human intervention that causes adverse impacts on activities (e.g. food production) or societal groups (e.g. farmers) (Dai, 2011). Drought often begins following a prolonged period of moisture deficiency (Lanen, 2006; Palmer, 1965) propagating through the hydrological cycle, exhibiting differing spatial and temporal characteristics depending on a variety of factors, for example, antecedent conditions and soil moisture (Heim, 2002; Todd et al., 2013). Wilhite and Glantz (1985)~~,~~ classified droughts into four types: meteorological, hydrological, agricultural, socioeconomic, with Mishra and Singh (2010) recommending the inclusion of a fifth classification ~~‘~~ground water~~’~~ drought. Drought has been referred to as a ‘creeping phenomenon’ (Mishra and Singh, 2010), and its impacts vary from region to region, with drought effects exacerbated by other meteorological elements, such as temperature, wind, and humidity (Brázdil et al., 2008). Palmer (1965, pp.1) notes that “drought means various things to various people, depending on specific interest”. Droughts are complex so-called ‘natural’ hazards – the term ‘natural’ in natural hazards, although etymologically doubtful, because in a sense all hazards are natural, may be considered as ‘natural’ as sanctioned by a long-term use in disaster research (Sangster et al., 2018), with droughts causing significant environmental, social and economic impacts (Van Loon et al., 2016). Drought is an international phenomenon with notable drought episodes throughout the twentieth and twenty-first centuries, e.g. 1930s ‘Dust Bowl’ in the USA (Schubert et al., 2004); 1975-76 in Europe (Parry et al., 2012; Zaidman et al., 20~~1~~02); China 1994 & 2010-2011 (Zhang et al., 2019) and South Africa 2015-17 accompanied by continued low rainfall (Wolski, 2018). Over the last decade a number of studies have started to explored historical droughts (Brázdil et al., 2009, 2018b) and the impacts experienced over decades to centuries on water resources (Lennard et al., 2015); agriculture (Brázdil et al., 2018a); infrastructure (Harvey-Fishenden et al., 2019); stream and river flows (Zaidman et al., 20~~1~~02); groundwater (Bloomfield and Marchant, 2013); with recent calls (e.g. Trnka et al., 2018) for more to be done with existing data, particularly in understanding past socio-drought responses and changes in vulnerability. Considerable work has been undertaken in recent decades in developing robust and long flood and drought chronologies using combinations of archival (Brázdil et al., 2018b; Yan et al., 2014; Zheng et al., 2006) and instrumental (Brázdil et al., 2009) sources from around the globe, although much work to date has focused on Europe (Wilhelm et al., 2018). The development of new online digitised sources has facilitated greater historical analysis (Black and Law, 2004; Wang et al., 2018) with greater recognition from regulatory authorities of the value of historical information (Kjeldsen et al., 2014).

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

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

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

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

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

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

2 Study Area

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

3 Data and Methods

3.1 Data sources

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

3.1.1 Documentary data

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

In addition to the meteorological sources identified, information from sources detailing agricultural activity provide valuable auxiliary reference materials, including the following items: Shenyang local records (Meng, 1989; Shenyang Municipal People's Government Local Records Office (1994-2011), 2011); The year of flood and drought in Shenyang from 1276 to 1985 (Shenyang Municipal People's Government Local Records Office, 1998). The following datasets have been acquired from the Office of State Flood Control and Drought Relief (1999); Farmland affected area from 1949 to 1990 in Liaoning Province Statistics on Drought Area of Heavy Drought in Liaoning Province; Drought rating assessment in various regions of Liaoning Province from 1949 to 1990; Drought Statistics in the Province from 1470 to 1949; Comparison of Precipitation in Liaoning Province from 1949 to 1964 and from 1965 to 1990; Comparison of grain yield per plant, drought frequency and drought reduction in various regions of Liaoning Province; hydrological station data for Liaoning Province; Regular frequency of continuous drought in dry season in Liaoning Province. Local newspapers have also been accessed to corroborate records of droughts e.g. the Shengjing Times (Shenyang was previously called Shengjing – see Table S1reflecting the old city name).

3.1.2 Instrumental data

Instrumental climate data are taken from two datasets, the first is long-term meteorological data, including monthly precipitation (05/1905 to 12/1988) from the Research Data Archives Computational & Information Systems Lab (NCAR, 1996), no records present for 1944-1946. The precipitation records for Shenyang have also been viewed and photographed in the Chinese Meteorological Archives in Beijing. This dataset covers long term records of 60 relatively evenly distributed stationssites in China, with long records. The second precipitation series was retrieved from the National Disaster Reduction Centre of China (NDRCC), which provides daily data for air pressure (parameter code: V10004), daily average temperature (V12001), daily highest temperature (V12052), daily lowest temperature (V12053), precipitation (V13201), average wind speed (V11002), sunshine hours (V14032), for the period 01/01/1961 to 31/05/2016. This study uses the precipitation data (V13201), however, subsequent drought analysis could use the additional data for more complex drought modelling. Analysis of these datasets permits varying temporal analysis of the precipitation, with a long overlap period that can be used to compare the association of these two data sets.

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

3.2 Data processing

3.2.1 Documentary data

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

In the process of analysing documentary sources for Shenyang, it is necessary to pay particular attention to historical changes to the name of Shenyang and the boarders of the provinces (see Table S1). For example, in the book "Zhong Guo Dong Bei Yu Dong Bei Ya Gu Dai Jiao Tong Shi" (Wang and Pu, 2016), it is noted that during the Han Dynastry, 'Liao Dong Jun' was used for the Shenyang area, whereas during the Dong Han Dynasty, the southern part of Shenyang continued to belong to Liao Dong Jun, and the northern part belonged to Xuan Tu Jun (Zhao, 2006). In addition, the Gao Xian region is the recent Sujiatun area in Shenyang (Wang and Pu, 2016); Yan (2012) detailed the historical changes in the Shenyang (Table S1).

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

iii. Information unclear - the disasters cause or event location is unclear. For example, in 1549, the drought and locust disaster occurred in Xingcheng County of Liaoning Province ("Ming Shi Zong Shi Lu", Vol. 353). In 1549 Xingcheng belonged to Liaoxi; however, Shenyang belonged to Liaodong, therefore, this record is not in the target region and is excluded.

iv. A record is excluded if it does not clearly state drought, or that a drought was the cause. Although there are many types of event that are associated/related to droughts, such as locusts, epidemic disease or famine, where historical records do not directly state drought or attribute the cause to drought they are excluded. For example, in October 1551, the Liaodong area did not collect grain tax because of disasters ("Ming Shizong Record", Vol. 3, 7:8). The record does not specifically state that a drought occurred though this is a common response to a drought.

3.2.2 Instrumental data

Data quality assessment and management of both long (NCAR) and shorter (NDRCC) series was required to ensure homogenisation and data suitability (see section 3.1.2). Total precipitation includes both liquid and equivalent frozen precipitation. All meteorological variables are recorded as one-tenth of their specific units (mm), but are converted to mm throughout. For both instrumental series, care and attention was taken with the original data series quality, with the data descriptors recorded in Table 2. At Shenyang meteorological station, missing data occurred eight times (representing 0.826% of the record), and rainfall was marked three times with 'R', reflecting monthly totals identical to the previous month, raising concerns as to the validity of the data (01-02/1906, 12/1908-01/1909 and 12/1968-01/1969).

There is a reduction of available meteorological data during the years 1943-46 following the Second World War ~~WWII~~ across much of eastern China, as such no suitable local sites could be identified to infill this series; for other missing monthly data, the monthly averages are included where single months are missing, as often other local stations also have missing data. For the shorter instrumental daily precipitation series (NDRCC), data descriptors are included in Table 2, including percentage of record impacted. ~~Since~~The precipitation record for Shenyang ~~Station~~ has four ~~records~~station ~~of~~ relocation's/instrument renewals during its monitoring record ~~in~~ (October 1970, October 1976, January 1989~~,~~ and June 2006)~~.~~.~~(Li et al., 2014), refer to the public data source Global Summary of the Month (GSOM) in NOAA website~~ An analysis of the homogeneity of the record was undertaken using the approach presented by Li et al. (2014), when assessing temperature changes in Shenyang. A~~, through the~~ correlation analysis of Shenyang ~~station~~with the ~~and its~~ nearby Benxi precipitation -station record ~~about the period of Shenyang relocation~~ (~41 km southeast of Shenyang) demonstrates a stable difference (prediction ration) between the two series for all periods and an R^2 throughout of >0.88 (Table S2)~~, it can be seen that the prediction ratio, relative change, and R^2 of the two stations are stable~~. In the absence of ~~obvious changes,~~any evident changes within the precipitation record resulting from localised station relocation/instrument renewal we consider the precipitation data at ~~it can be thought that the relocation station has little interference with the recorded rainfall in~~ Shenyang to be homogeneous~~, and the data quality is~~ and reliable.

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

04/1964, 285.9 mm, with an average normally of c. 50 mm. An analysis of the variability in the precipitation is presented (Figure 4), with the lowest precipitation (the driest, 1913: 341.1 mm a^{-1}) and highest (wettest) years noted (1923: 1064.9 mm a^{-1}; Figure 4a); a seasonal analysis and long term trend are also presented (Figure 4b-e) with a 30-year Savitzky-Golay filter (Savitzky and Golay, 1964).

3.3 Drought Identification

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

3.3.1 Standardized Precipitation Index (SPI)

A number of drought indices have been developed Heim (2002). Meteorological drought indicators can be divided into two categories focused on either the physical mechanisms of drought or the statistical distribution of meteorological elements; the SPI belongs to the latter group and is widely used (Lennard et al., 2015; Mckee et al., 1993). As the long precipitation series includes only monthly data, the Standardised Precipitation Index (SPI) is used, this index has a number of advantages when used over long timescales compared to other potential drought indices. The SPI developed by Mckee et al., (1993), is a widely applied meteorological drought index that quantifies precipitation deficits or excess across different climates at multiple timescales, typically of 1–24 months, however the simplicity of the SPI (precipitation as the only input) causes some limitations too, e.g. no consideration of evaporative demand (Vicente-Serrano et al., 2014). SPI values are dimensionless units, with negative values indicating drier than normal conditions and positive values wetter than normal conditions. Drought onset is generally assumed to occur at SPI values exceeding ≤1, however the National Standards of the People's Republic of China (2017) classification uses ≤0.50 as indicative of drought onset, with drought termination identified as when SPI returns to ≥0 (Table 3a); within this study we apply the classification as defined for China. SPI can be used to characterise drought duration, severity and timing of onset and termination (together known as the drought structure e.g. Noone et al., (2017)), based on the classifications identified in Table 3a; the SPI classification recommended in China (National Standards of the People's Republic of China, 2017) differs slightly from that of the WMO (2012; Table 3 (a and c), though others have also proposed regionally specific SPI versions based on Mckee et al. (1993) e.g. Moreira et al. (2008)

for Portugal. Drought duration is determined by the number of months between drought onset (SPI ≤0.49) and termination (SPI ≥0), drought severity is categorised using the SPI classification system with peak severity the minimum SPI value recorded during the drought. Within this study SPI will be examined at three temporal scales SPI-1 (1 month), SPI-6 (6 months), and SPI-12 (12 months) (Figure 5a-c). The SPI was determined by fitting a probability density function to selected accumulation periods using L-moments to estimate parameters. A gamma probability density distribution was found to be the most appropriate fit, using a Kolmogorov-Smirnov (K-S) test to compare empirical and theoretical fit, calculating the cumulative probability. This was then converted into the standard normal distribution, with transformation of the cumulative probability of the fitted distribution to standard normal distribution to define the SPI value (Lloyd-Hughes and Saunders, 2002; Vicente-Serrano et al., 2010). Other univariate distributions have been recommended where a gamma distribution is not appropriate (Barker et al., 2016; Stagge et al., 2015).

3.3.2 Documentary analysis

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

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

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

3.3.3 Drought trend and frequency analysis

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

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

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

4 Results and Discussion

4.1 Temporal analysis of instrumental time series

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

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

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

4.2 Drought classification and trends

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

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

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

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

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

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

and,

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

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

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

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

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

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

4.3 Societal vulnerability to droughts

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

4.4 Contemporary droughts and generating mechanisms

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

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

5 Summary

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

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

Data availability

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

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Competing Interests

None

Author Contribution

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

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Ming Shi Zong, Vol. 3, 7:8

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

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

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

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

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

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

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

Table 4. Drought class and phenomenon comparison table

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

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

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

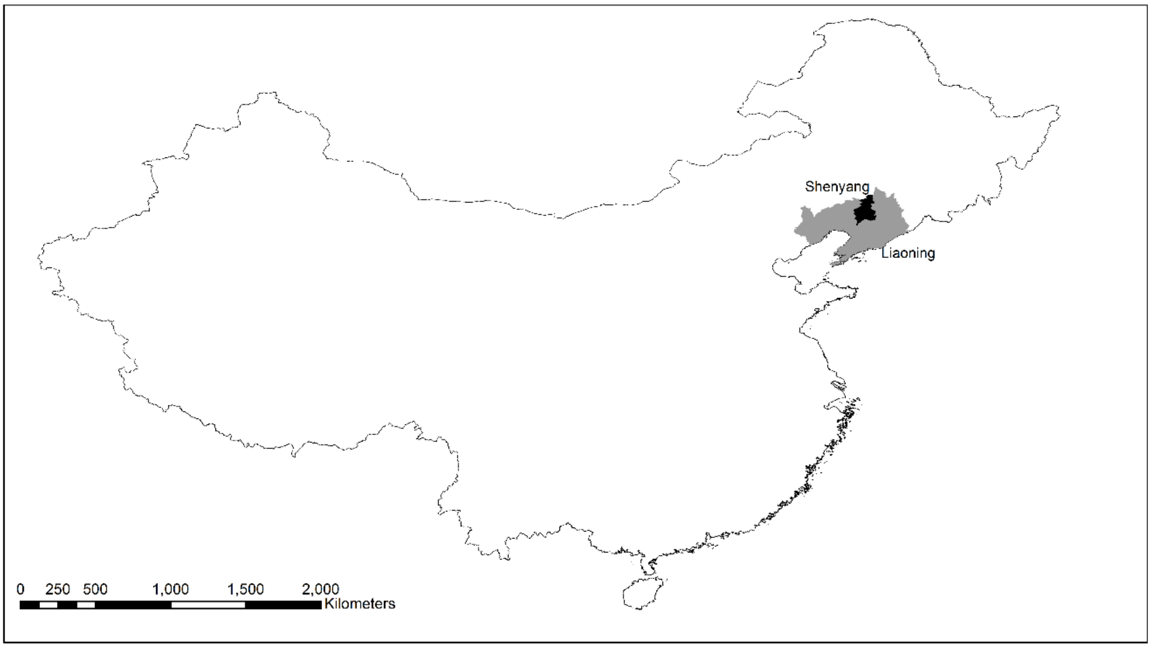

Figure 1. The geographical location of Shenyang, Liaoning P~~p~~rovince and mainland China

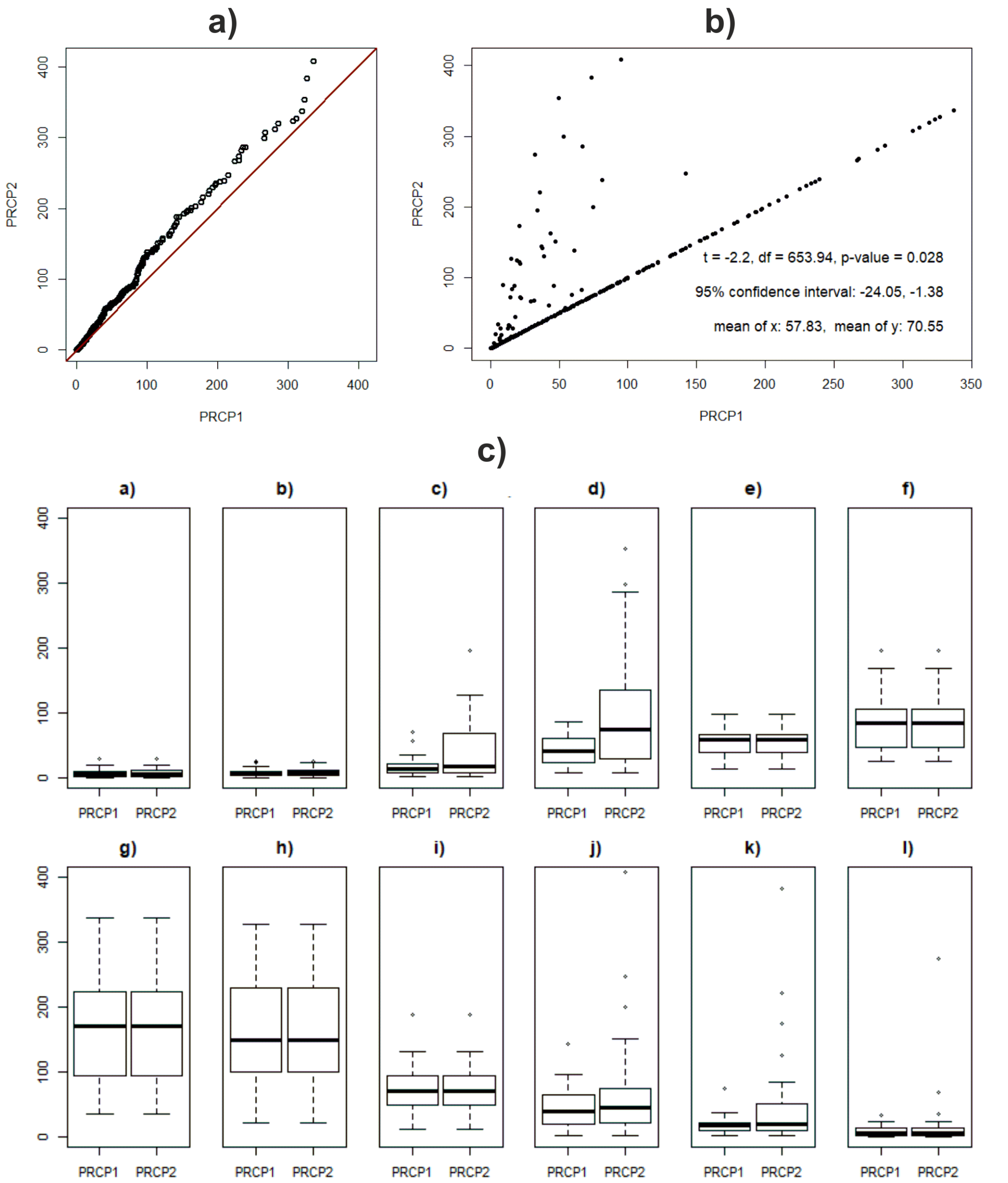

Figure 2. a) QQ plot of two precipitation (mm) data sources (p-value 0.028); b) monthly precipitation comparison of two datasets (significance Analysis of Precipitation from 1961 to 1988); c) monthly precipitation distribution and outliers (a-l: January to December)

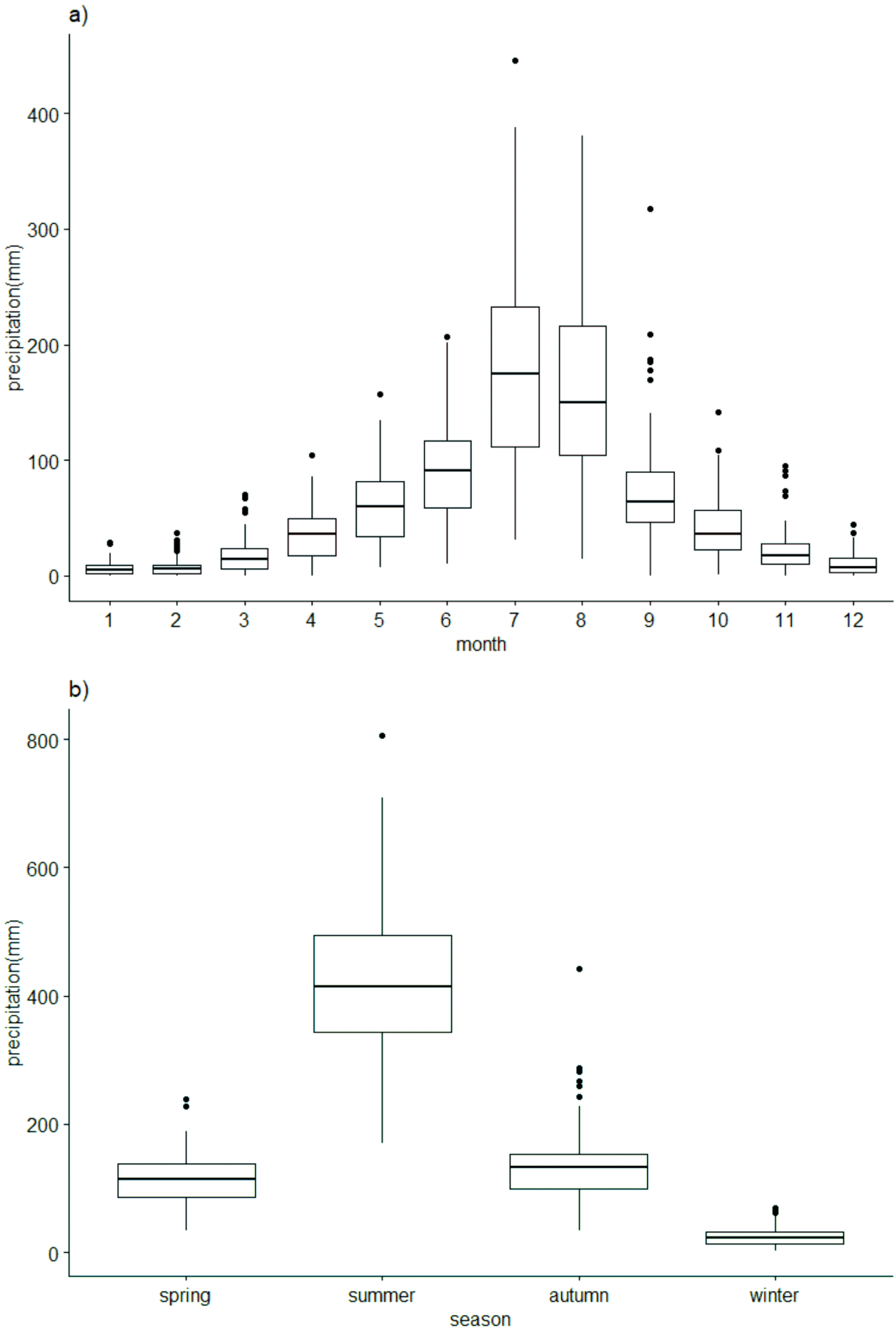

Figure 3. 1906-2015 Monthly and seasonal precipitation box chart

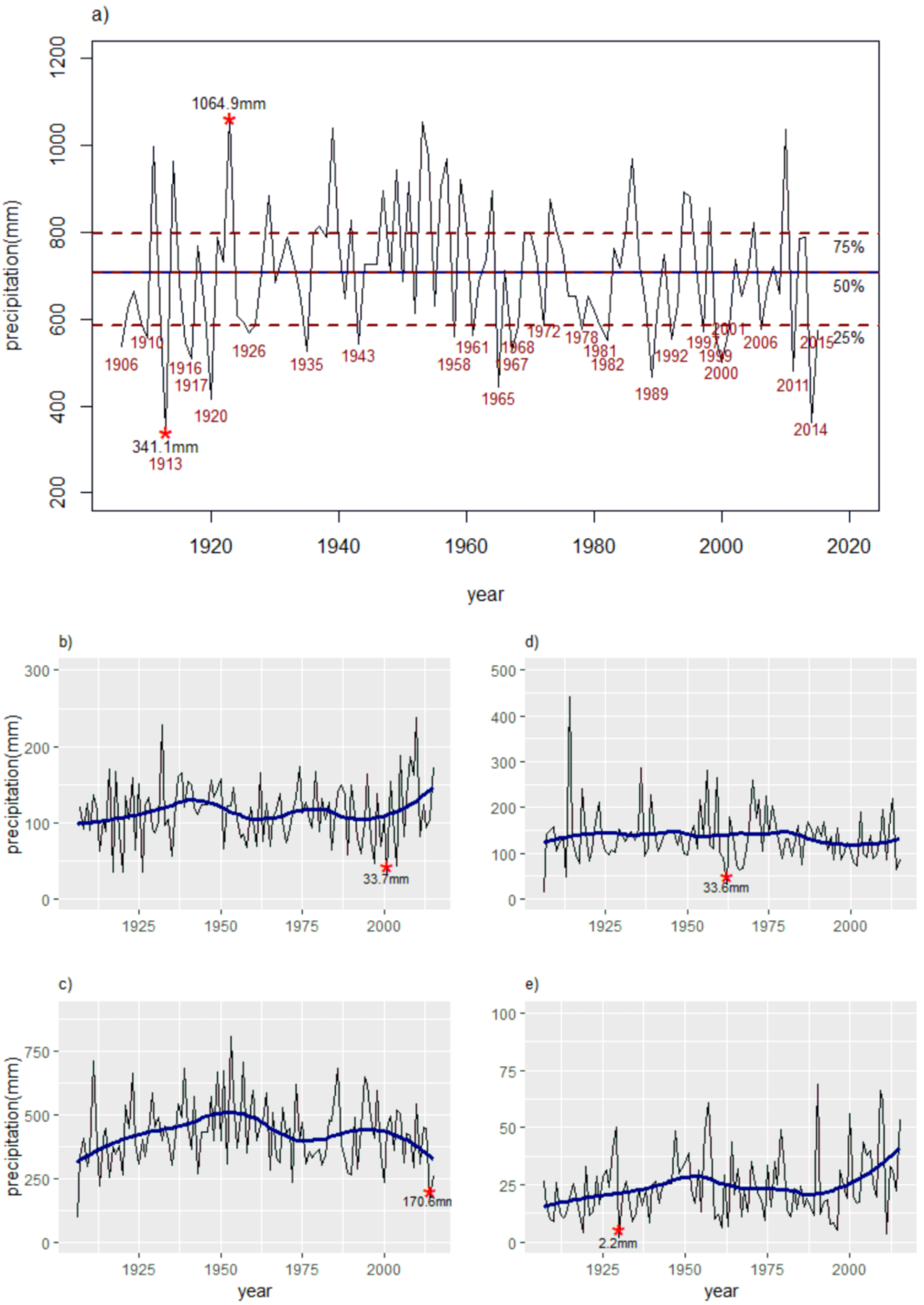

Figure 4. Annual and seasonal precipitation from 1906 to 2015, a) annual (quartiles indicated by dashed lines); b) spring; c) summer; d) autumn; and, e) winter. A 30-year Savitzky-Golay filter is presented (bold line b-e).

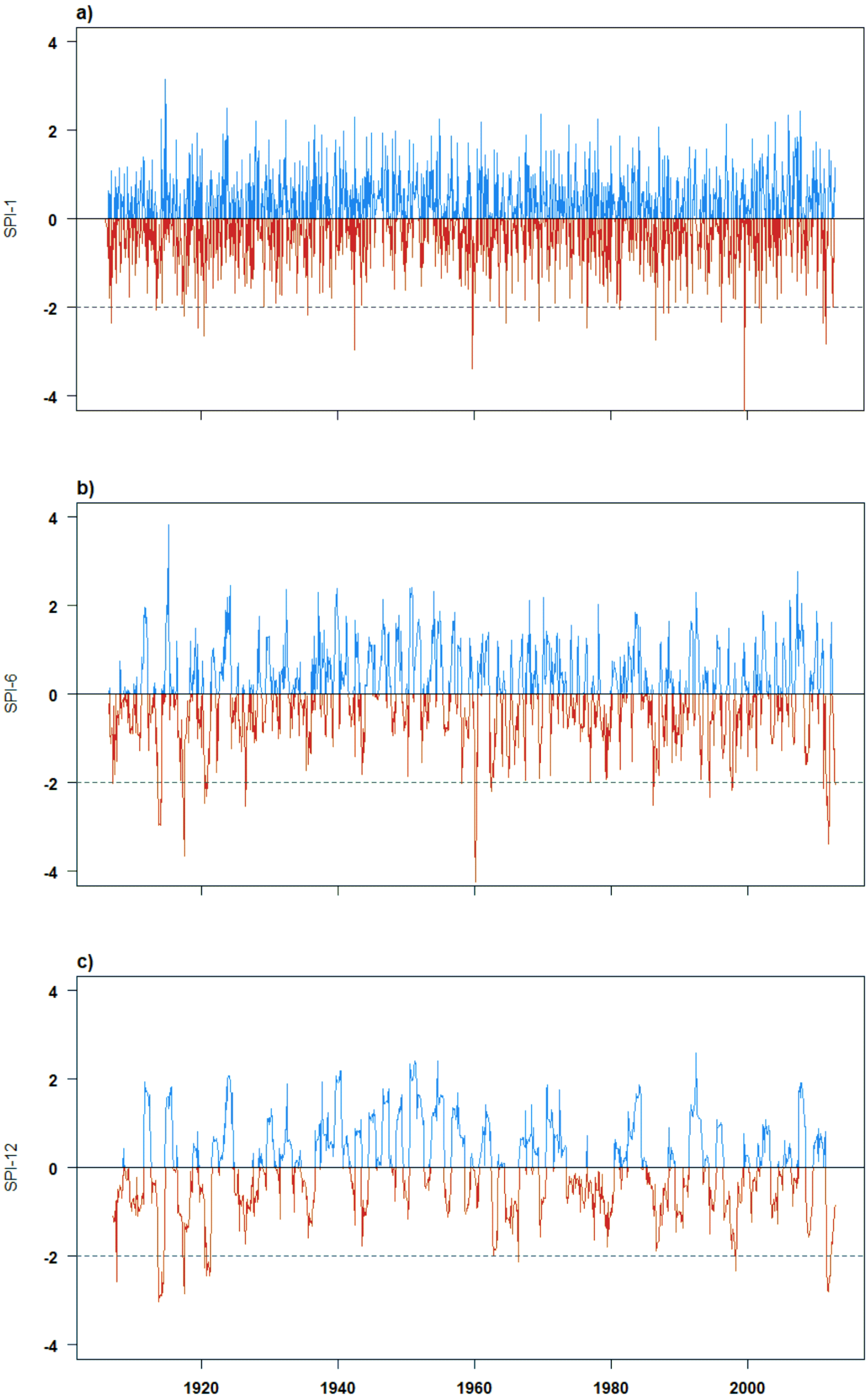

Figure 5. Standard Precipitation Index from 1906 to 2015, with wetter (blue) and drier (red) than normal conditions indicated for a): SPI-1; b) SPI-6; and, c) SPI-12

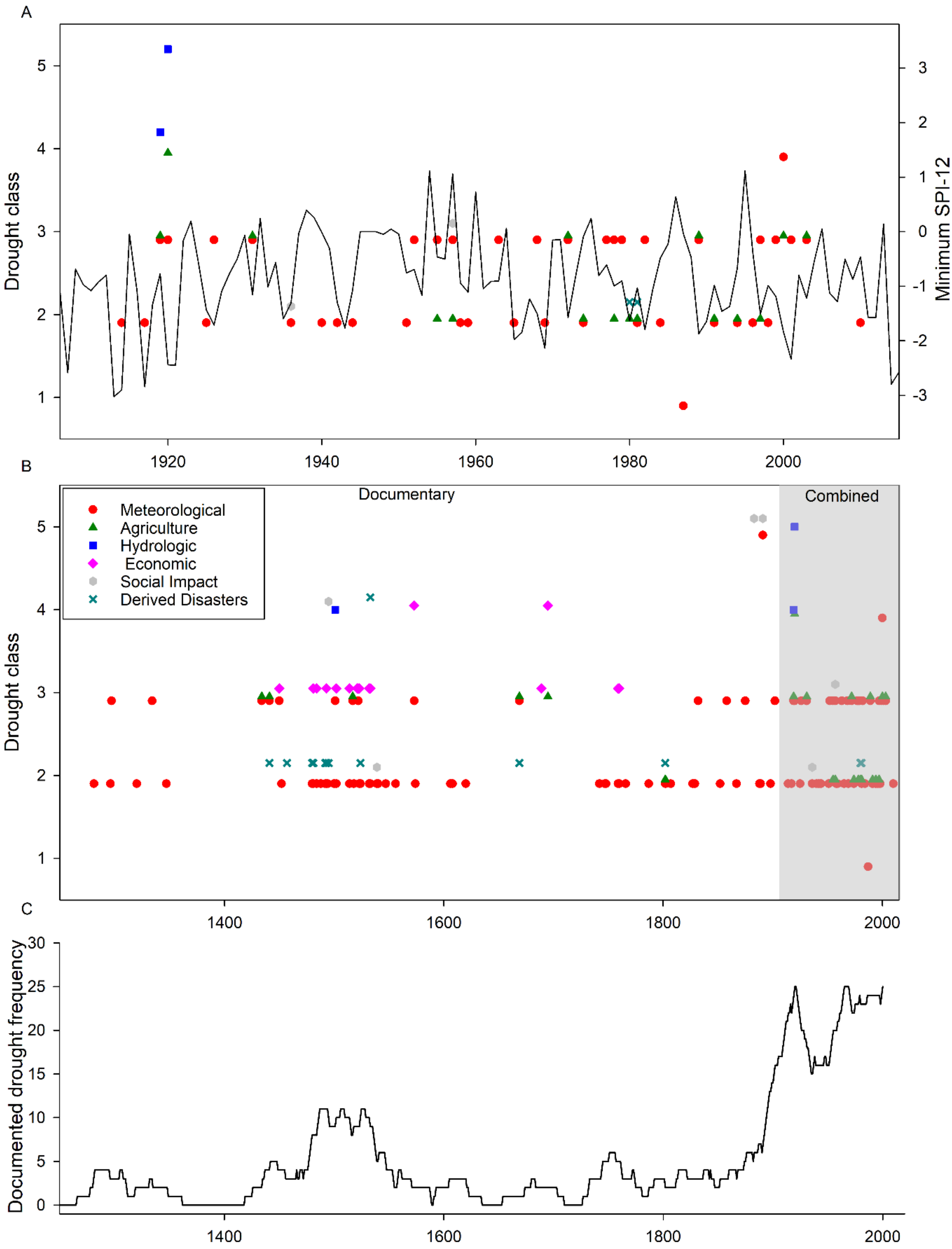

Figure 6. Shenyang drought classification (colour/shape) for a) combined archival and instrumental period (1906-2015) with minimum annual SPI-12; b) augmented period (1200-2015); and, c) a running 30-year mean drought frequency (1200-2015).

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

Reply to reviewer comments

Dear Professor Grab,

Professor Macdonald a native English speaker has been through the paper whilst on paternity leave to edit and correct the sentence structure and grammar of this article. We hope that you are satisfied with our revised version.

Yours sincerely,

LingYun, Neil, Heather, Richard and Rachel

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

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

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, ~~and~~ with a variety of definitions ~~for drought~~ in operational use around the world.~~,~~ T~~t~~here is no single universal definition ~~for of~~ defining what constitutes a drought, with a variety of definitions ~~used around the world~~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 ~~are a long-term water deficit, that~~ often develop~~s~~ slowly under natural conditions or through human intervention, ~~that~~ causing~~es~~ adverse impacts on activities (e.g. food production) or societal groups (e.g. farmers) (Dai, 2011). Droughts often begin~~s~~ following a prolonged period of moisture deficiency (Lanen, 2006; Palmer, 1965), propagating through the hydrological cycle, exhibiting differing spatial and temporal characteristics dependent~~ing~~ on a variety of factors, ~~for example,~~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~~e.g.~~ 1930s ‘Dust Bowl’ in the USA (Schubert et al., 2004); 1975-76 in Europe (Parry et al., 2012; Zaidman et al., 2002); China in 1994 & 2010-2011 (Zhang et al., 2019) and South Africa in 2015-17 ~~accompanied by continued low rainfall~~ (Wolski, 2018). Over ~~the~~ recent ~~last~~ decades ~~a number of~~ several studies have started to explored historical droughts (Brázdil et al., 2009, 2018b) and their associated impacts ~~experienced~~ 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)~~; with r~~Recent calls (e.g. Trnka et al., 2018) in historical climatology have called for more analysis to be ~~done~~ undertaken with existing data, particularly in understanding past socio-drought responses and changes in vulnerability. Considerable work has been undertaken in recent decades in developing robust ~~and~~ long flood and drought chronologies, using combinations of archival (Brázdil et al., 2018b; Yan et al., 2014; Zheng et al., 2006) and instrumental (Brázdil et al., 2009) sources from around the globe;~~,~~ although much work to date has focused on Europe (Wilhelm et al., 2018). The development of new online digitised sources has facilitated greater historical analysis (Black and Law, 2004; Wang et al., 2018) with ~~greater~~ increased recognition from regulatory authorities in~~of~~ the value of historical information (Kjeldsen et al., 2014).

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

This paper examines the history of drought in the Shenyang region of Northeast China, it considers the spatial and temporal variability ~~in~~ of droughts, ~~the~~ assesses drought characteristics ~~of droughts, and~~ examines drought causing climatic conditions and ~~mechanisms responsible and~~the impacts of past droughts on society. Our objectives are:

ix. To develop and analyse ~~the~~ a record of droughts and ~~the documentary evidence for~~ 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);

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

xi. 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,

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

2 Study Area

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

3 Data and Methods

3.1 Data sources

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

3.1.1 Documentary data

The 'A compendium of Chinese Meteorological Records of the Last 3,000 Years' produced by Zhang (2004) and updated in 2013, summarises 7835 historical sources from the earliest existent materials in the Chinese language, the 'Oracle Bones Collection' (c.1600 BC) through to more recent sources which describe meteorological incidences in China. The 'Oracle Bones' have a long history of being studied for meteorological information, with early studies undertaken by Wittfogel (1940). There are also a small number of private diaries and court memorial files of the Qing Dynasty, though the 'History of Drought Archives in the Qing Dynasty' (Tan, 2012) provides a summary of the collection spanning from 1689 to 1911, with more than one million pieces present in the Qing Dynasty palace archive. The China Meteorological Disasters Ceremony (Liaoning volume) from Wen et al. (2005) provides detailed accounts of droughts, together with associated disasters ~~alongside records of other disasters which may have been~~ 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 ~~been placed into~~focused on collating ~~the~~ archival materials present across China that detail~~ing~~ natural hazards, this wealth of information provides valuable opportunities for further exploration~~; h~~. 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; 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; r~~R~~egular frequency of continuous drought in the dry season in Liaoning Province. Local newspapers have also been accessed to corroborate records of droughts, ~~e.g.~~such as the Shengjing Times (Shenyang was previously called Shengjing – see Table S1).

3.1.2 Instrumental data

Instrumental climate data are taken from two datasets, the first is long-term meteorological data, including monthly precipitation (05/1905 to 12/1988) from the Research Data Archives Computational & Information Systems Lab (NCAR, 1996), no records 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), sunshine hours (V14032), for the period 01/01/1961 to 31/05/2016. This study uses the precipitation data (V13201).~~,~~ H~~h~~owever, subsequent drought analysis could use ~~the~~ additional meteorological variables ~~data~~ for more complex drought modelling. Analysis of these two datasets permits a ~~varying~~ temporal analysis of the reconstructed long-term precipitation series, with a long overlap period ensuring ~~that~~ a statistical comparison of the datasets can be made~~can be used to compare the association of these two data sets~~.

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

3.2 Data processing

3.2.1 Documentary data

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

In the process of analysing documentary sources for Shenyang, it is necessary to pay particular attention to historical changes to the name of Shenyang and the ~~boarders~~ ~~borders of the~~ province boundary~~s~~ (see Table S1). For example, in the book “Zhong Guo Dong Bei Yu Dong Bei Ya Gu Dai Jiao Tong Shi” (Wang and Pu, 2016), it is noted that during the Han ~~Dynastry~~Dynasty, ‘Liao Dong Jun’ was used for the Shenyang area.~~,~~ ~~whereas~~ 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 ~~recent~~ Sujiatun area in Shenyang (Wang and Pu, 2016); Yan (2012) detailed ~~the~~ historical changes in the Shenyang (Table S1).

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

v. Information unclear - the cause of the disaster~~s caused~~ or event location ~~is~~are unclear. For example, in 1549, ~~the~~ a drought and locust disaster occurred in Xingcheng County of Liaoning Province ("Ming Shi Zong Shi Lu", Vol. 353). In 1549 Xingcheng belonged to Liaoxi; however, Shenyang belonged to Liaodong.~~,~~ T~~t~~herefore, this record is not in the target region and is excluded.

vi. A record is excluded if it does not clearly state drought, or that a drought was the cause. Although there are many types of event that are associated/related to droughts, such as locusts, epidemic disease or famine, where historical records do not directly state drought or attribute the cause to drought they are excluded. For example, in October 1551, the Liaodong area did not collect grain tax because of disasters ("Ming Shizong Record", Vol. 3, 7:8). The record does not ~~specifically~~ explicitly state that a drought occurred though this is a ~~common~~ typical response to ~~a~~ drought, therefore the record is excluded.

3.2.2 Instrumental data

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

Analysis of the two series for the coeval years of record (1961-1988) was undertaken, a Q-Q plot ~~was undertaken~~ ~~attempted to~~ verify that both data sources are normally distributed (Figure 2a). Figure 2b shows a ~~good~~ linear distribution (p-value of 0.028); however, differences between the series exist. During the period 1961-1988, the average difference between the two datasets is 12.72 mm, and the maximum is 313.2~~, which occurred in~~ (October 1974); further examination reveals that all the ~~differences~~ variations occur~~ring~~ in the period 1961-1979, with the two datasets producing identical values for all months from 1980 onwards, this replicability in the later records provides confidence in extending the NCAR dataset through to the present

(2015). Analysis of the dispersion and outliers for each month was also undertaken (Figure 2c), the months with the greatest discrepancy are March and April, possibly reflecting challenges in the~~of~~ recording of snow/ice fall. Comparison of the monthly and seasonal precipitation patterns presented in Figure 3 for Shenyang for the period 1906-2015 using the new augmented series ~~illustrates that~~identifies some ~~of the anomalous~~ abnormal values from the NDRCC data from the period 1961-1979, which appear unrealistic, e.g. 04/1964, 285.9 mm, with an average ~~normally~~ usually of c. 50 mm. An analysis of the variability in the precipitation is presented (Figure 4), with the lowest precipitation (the driest, 1913: 341.1 mm a^{-1}) and highest (wettest) years noted (1923: 1064.9 mm a^{-1}; Figure 4a); a seasonal analysis and long term trend are also presented (Figure 4b-e) with a 30-year Savitzky-Golay filter (Savitzky and Golay, 1964).

3.3 Drought Identification

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

3.3.1 Standardized Precipitation Index (SPI)

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

3.3.2 Documentary analysis

Documentary data provides additional ~~information~~ detail beyond that offered by instrumental series, providing valuable information ~~detailing~~ reflecting both societal impacts and responses to past events (Pfister, 2010). At Shenyang, the first recorded drought occurs in 347 AD;~~,~~ but, only three events are recorded during the period 347-1200;~~,~~ therefore the records analysed within this paper start post-~~-~~1200, as the frequency of records increases. Previous studies (e.g. Brázdil et al., 2009; Hanel et al., 2018; Todd et al., 2013) using historical archival sources have examined qualitative records and used a variety of different indices or grades of drought. The use of an ordinal index systems for the classification of descriptive accounts in historical climatology is common, with a range of classes used, such as ~~e.g~~. Nash et al., (2016) who used a +2 to -2 classification in examining wet/dry phases in Natal and Zululand in Southern 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~~ in China~~ (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 ~~are~~ 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 few accounts detail groundwater droughts within the historical records, as such ~~(~~they are incorporated into hydrological droughts~~y~~ within this study. S~~), with the s~~ocio-economic ~~class~~droughts are~~ being~~ split into economic (impacts of ~~clear~~ precise cost) and social impact (impacts on people, e.g. health). In ~~splitting~~ 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~~, in the historical record examining these aspects can be examined considered in greater depth~~. Each of the different classes of drought has varying degrees of ~~increases in~~ impact severity (Table 4), in documenting each of these an assessment of the interrelationship between different types of impact can be made, for example, the point at which food relief may be initiated, or tax payments suspended (typically class 2/3), others such as praying for rain/snow are associated with high classes (4/5), reflecting personal, community and governmental responses (e.g. government control of food prices).

Annual drought values for the instrumental period (1906-2015) are represented by the minimum SPI-12 value within each calendar year; within the documentary accounts~~,~~ the most severe class of drought is used to determine the classification. We opted to use the SPI-12 in preference to SPI-6 (or shorter timescales), as precipitation in Shenyang has such a strong seasonal skew toward the summer months~~,~~. U~~u~~se of SPI-12 also permits a ~~stronger~~ 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 ~~combined~~ reconstructed ~~long-term~~ drought series for Shenyang (1200-2015) permits an analysis of ~~the~~ long-term drought trends and patterns. ~~Clearly, o~~Over such ~~a~~ long timescales~~,~~ a number of socio-political and cultural changes ~~will~~ have occurred (Bavel et al., 2019), which may influence the ~~extent or severity of a particular drought and the~~ capacity a population ~~has~~

to respond to a drought of any given magnitude or severity (Keenan and Krannich, 2010; Kreibich et al., 2019; Mechler and Bouwer, 2015). Human interventions may mitigate and/or exacerbate the impacts of drought downstream, through hydrological system management and engineering (He et al., 2017). The socio-political and cultural circumstances during each recorded drought ~~will~~ represent an ~~important~~ essential underpinning in considering long-term drought trends and variability and are~~. They~~and ~~will be~~ considered individually in each instance (see discussion by Brázdil et al., 2020).

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

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

4 Results and Discussion

4.1 Temporal analysis of instrumental time series

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

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

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

4.2 Drought classification and trends

The reconstruction of historical droughts in Shenyang is divided into two parts. The first obtains drought class information from the SPI for the period 1906-2015 from an augmented instrumental series. The second uses historical documents and is defined based on specific classification criteria shown in Table 2, producing a long drought reconstruction from 1200 AD to 2015, with a 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 records 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.~~;~~ A~~a~~s 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 N~~n~~orth ~~Amercia~~ 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). ~~A number of~~Several droughts ~~occurring~~ are identified in the period 1750-1880 AD ~~are documented~~; however, the frequency and severity of droughts increases ~~thereafter~~ 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 ~~this is~~are not evenly distributed with most (66%) ~~of those events~~ occurring in the period 1906-1921 (1907, 1913-14, 1916-18 and 1920-21), with only three severe <-2 (SPI-12) droughts events after 1921 in Shenyang in 1968-9, 1999-2002 and 2014-15 (Figure 6a). The documentary accounts in the period 1906-2015 provide valuable corroborative evidence when compared to the annual minimum SPI-12 data, with most documentary accounts identified ~~recorded~~ as class 2 and 3, with few events classified as either 1, 4 or 5.~~,~~ ~~although~~ However, the presence and magnitude of the early droughts in the period 1906-21 are corroborated with documentary accounts classed as 4 and 5, with documentary evidence in 2002 also supporting a class 4 drought.

The types of drought recorded within the records are indicated in Figure 6b, ~~and~~ 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 class 2 and 3 (Figure 6b). The absence of deaths being documented restricts the number of class 5 socio-droughts, although the drought of 1920-21 is documented as a class 5 hydrological drought, the only documentary class 5 event in the twentieth century. It may be that ~~such~~ information detailing the most severe aspects of past droughts was not published, and/or that the droughts within the Liaoning province did not lead to such severe impacts, as few events prior to the late ~~nineteenth~~ nineteenth-century approach class 5. In focussing on the city of Shenyang, there is also a risk that the impacts differed within the city to those experienced in rural communities within the province, thereby reducing the number of agricultural droughts documented. Future works should, therefore, focus at the provincial scale to incorporate a ~~wider~~ 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 *post-industrial* (Chester et al., 2012; White, 1974) during the period of study presents challenges in assessing and comparing impacts. Recent droughts of comparable meteorological severity, e.g. 2014 (SPI-12: -2.8) to those of the early twentieth century, namely 1907 (-2.6), 1917 (-2.8) or 1921 (-2.5) illustrate how the responses and resulting impacts potentially ~~differed~~changed. In analysing these events the consequences of the droughts differed considerably, whilst ~~these~~ they~~events~~ do not record deaths among the population in Shenyang and/or Liaoning province they are severe, with the 1920-21 drought described as "Spring drought for several months, well and river ~~dry~~ dries up, the land ~~dry~~ dries up, no harvest at all, winter disaster victims everywhere, people live in hunger, and coild move out from the mountain village, village empty" [class 4 socio-drought but class 5-hydrological] (Office of State Flood Control and Drought Relief, 1999, p.388), across China an estimated 500,000 people died (Edwards, 1922). Analysis of the international media at the time reporting on the event is shaped by the socio-political circumstances, with The Times (London) recording 3 million as being displaced (9 Nov. 1920 p.11); however, as Fuller (2011) importantly notes this is often viewed from an international perspective, with local relief providers often failing to receive recognition. The responses to the drought varied~~,~~ but included those responses expected within an *industrial* framework, with both national and international relief occurring, but also local support complimenting *pre-industrial* responses, with the Shengjing Times (1920) reporting on the 1st July that "Chief Zhang set up an ~~alter~~ altar begging for rain" (6080, p.4). However, as Li (2007) notes in north China, population increases without apparent agricultural intensification or expansion during the late nineteenth century may have contributed to an increased susceptibility to drought associate harvest fluctuations. In comparison, during the 2014 drought which resulted in a Level III emergency response, itself a notable difference from 1921~~0~~ 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 section 4.1); water transfer of 400,000,000 m^3 from the Hun River, securing domestic and agricultural provisions (Sun, 2015); and the provision of relief service teams to support local infrastructure improvements, e.g. drilling new wells and supply ~~or~~ of water to over 32,000 people suffering shortages (Wang, 2014). The impacts of the drought were widely reported in the media, with

~~notably~~ notable commentary focused on the impacts to water supplies and food production: “Food production in Liaoning… estimated to decline by 5 billion kg this year” (China Daily, 2014). Whilst both events 1920-21 and 2014 were severe droughts, the relief planning and coordinated effort coupled with improved infrastructure and a more stable socio-political environment facilitated a more efficient response.

4.4 Contemporary droughts and generating mechanisms

Analysis of contemporary droughts through coupled documentary sources and SPI provide valuable insights into the importance of drought severity and duration on associated impacts. The ‘severe drought’ as defined by the SPI of 1968 (SPI-12: -2.13, duration 26 months) appears to have a relatively limited impact in Liaoning province, with few accounts recording particularly notable impacts beyond reduced agricultural output, whereas, interestingly, the drought of 08/1979-07/1983, whilst not 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 07/1999-04/2002 (SPI -2.3, duration 34 months) receives similar levels of documentary coverage to that of 1979-83 and 07/2014-15 (SPI -2.8; 18 months, but extends beyond the end of the record) 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 ~~dry previous~~ 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 materialising in summer/autumn;~~,~~ therefore, the correlation with summer and autumn ENSO3.4 is a reflection of a longer lagged drought accumulation process.

5 Summary

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

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

Data availability

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

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Competing Interests

None

Author Contribution

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

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

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

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

Table 2. Data Information Description Table

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

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

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

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

Table 4. Drought class and phenomenon comparison table

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

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

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

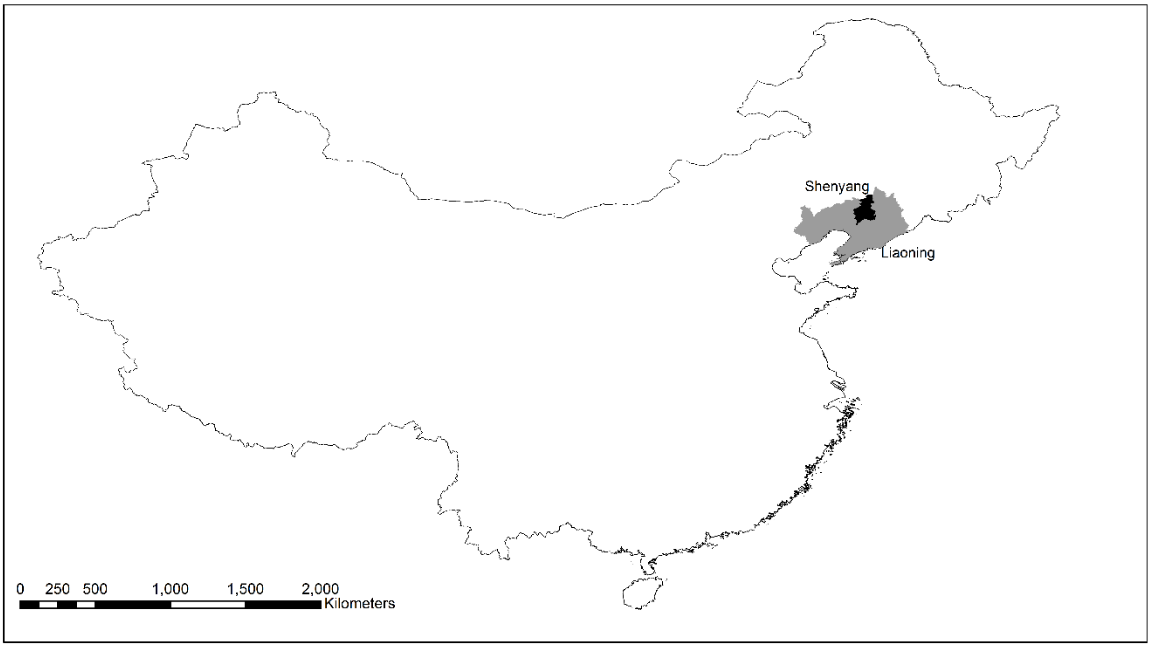

Figure 1. The geographical location of Shenyang, Liaoning Province and mainland China

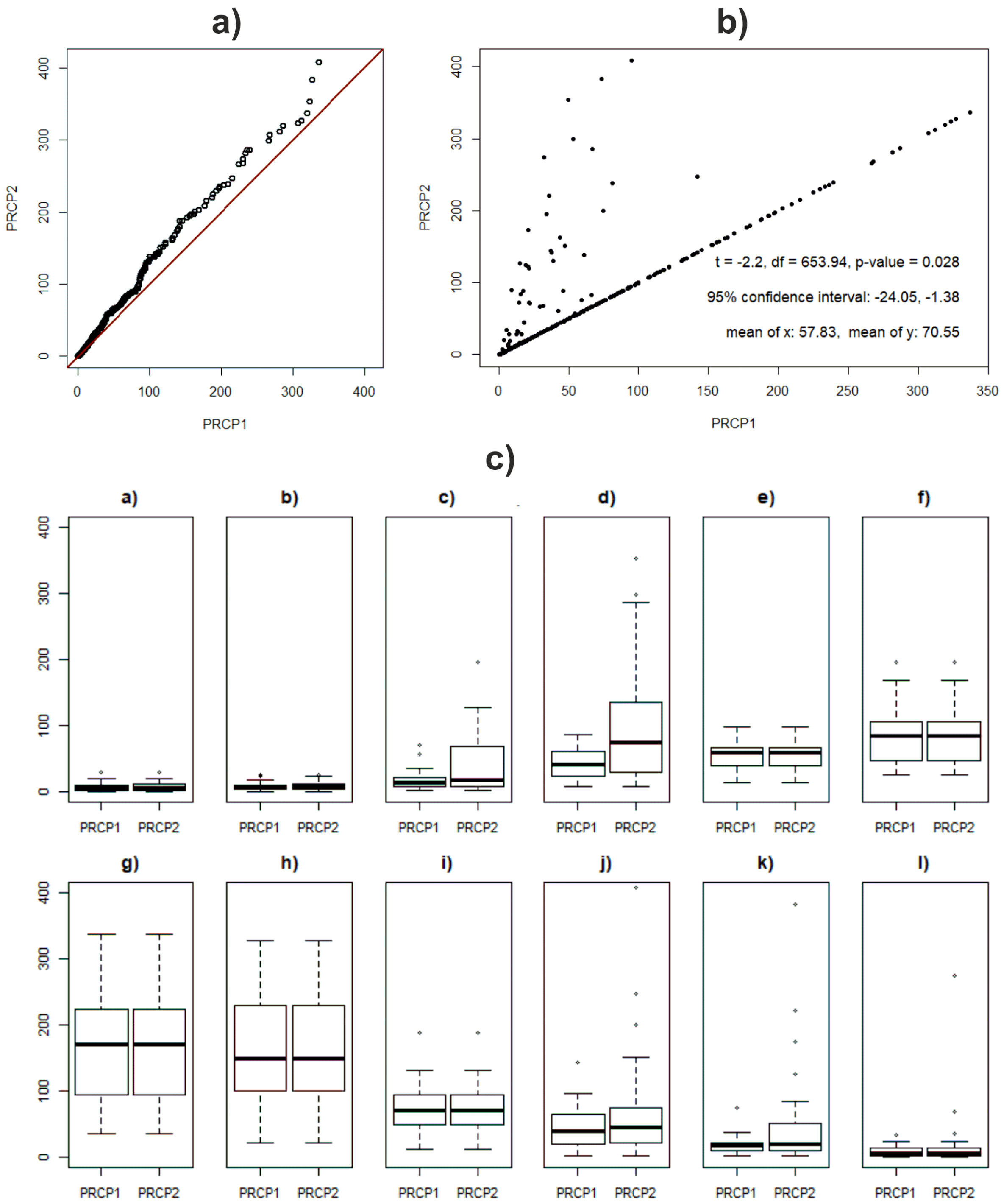

Figure 2. a) QQ plot of two precipitation (mm) data sources (p-value 0.028); b) monthly precipitation comparison of two datasets (significance Analysis of Precipitation from 1961 to 1988); c) monthly precipitation distribution and outliers (a-l: January to December)

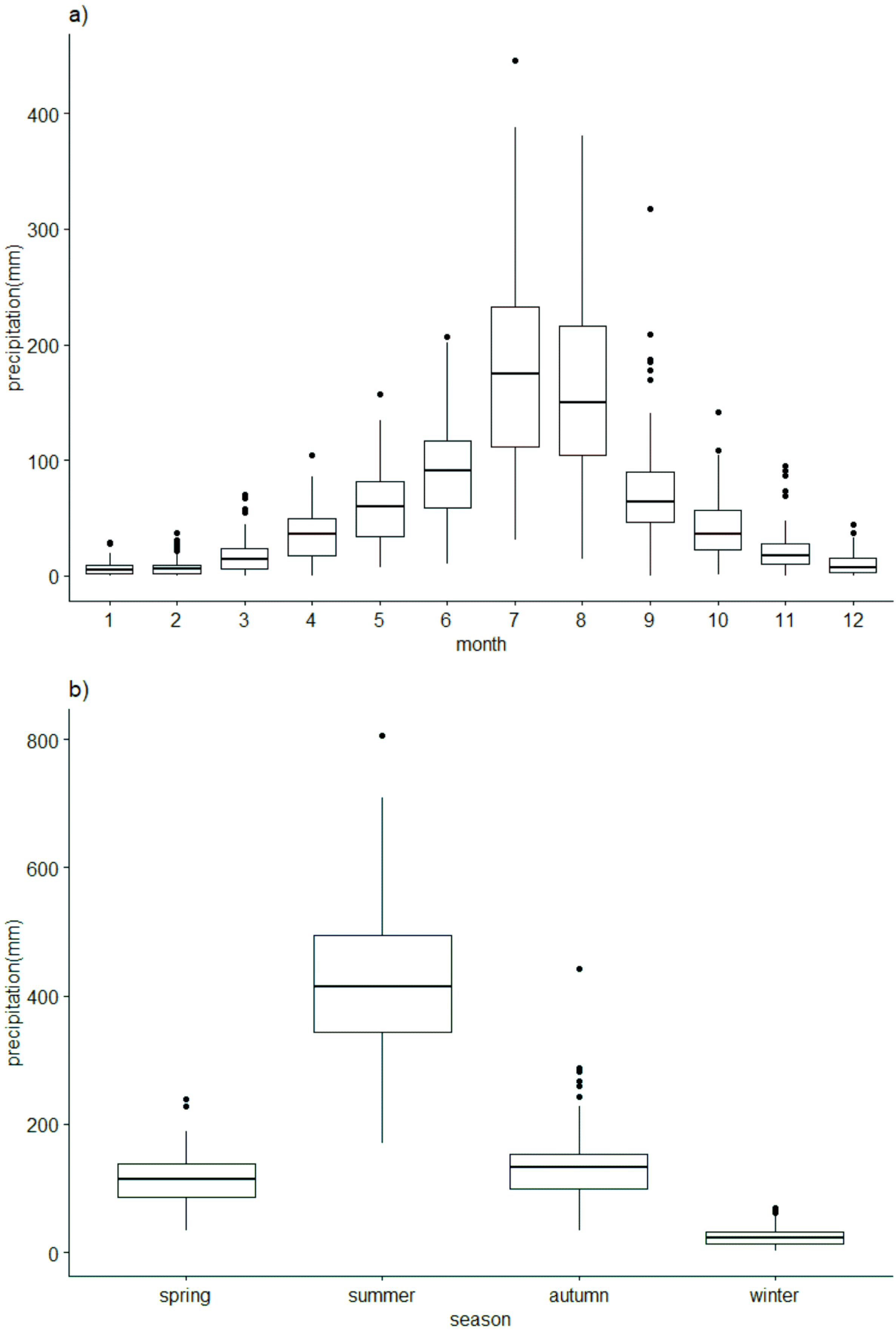

Figure 3. 1906-2015 Monthly and seasonal precipitation box chart

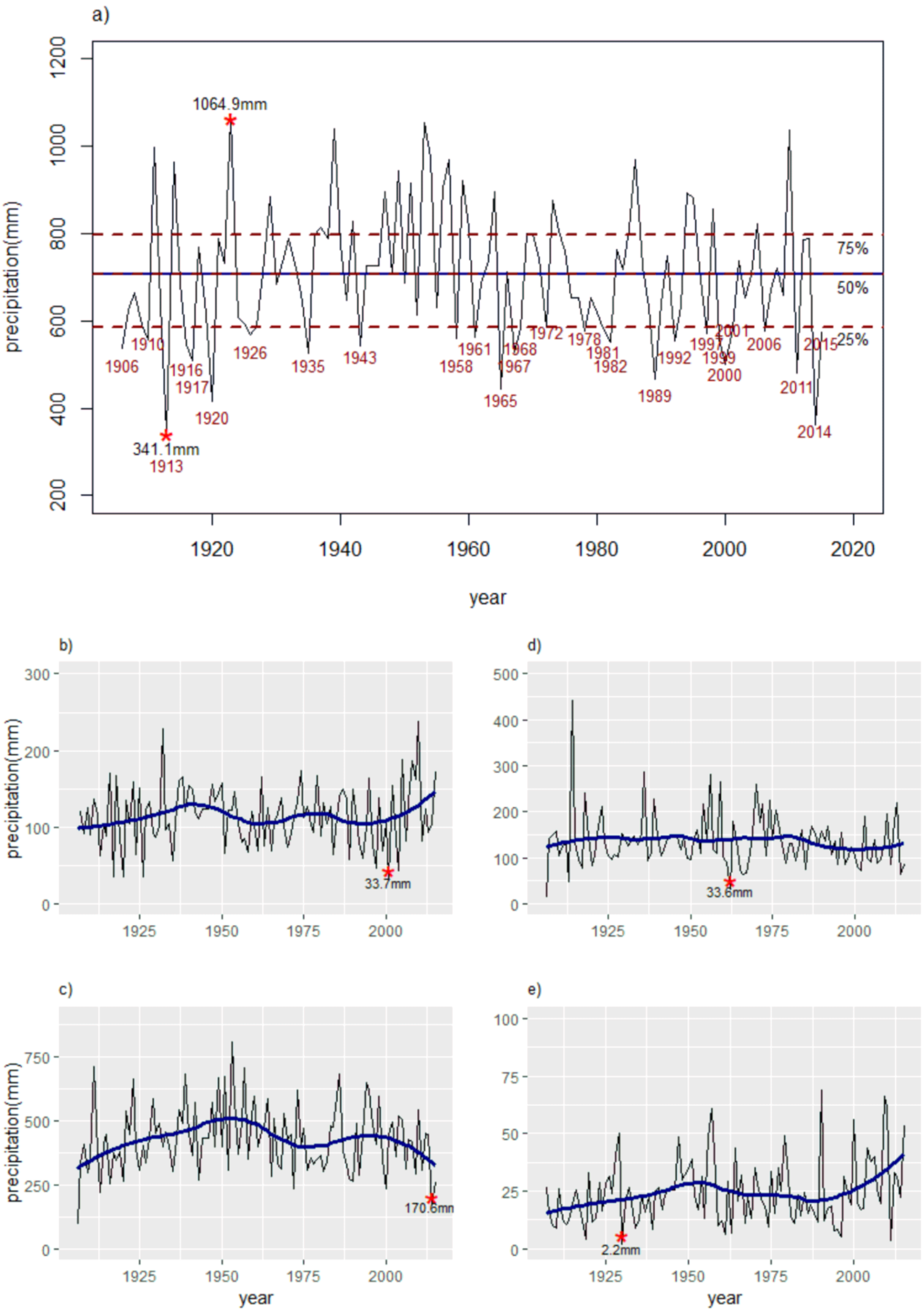

Figure 4. Annual and seasonal precipitation from 1906 to 2015, a) annual (quartiles indicated by dashed lines); b) spring; c) summer; d) autumn; and, e) winter. A 30-year Savitzky-Golay filter is presented (bold line b-e).

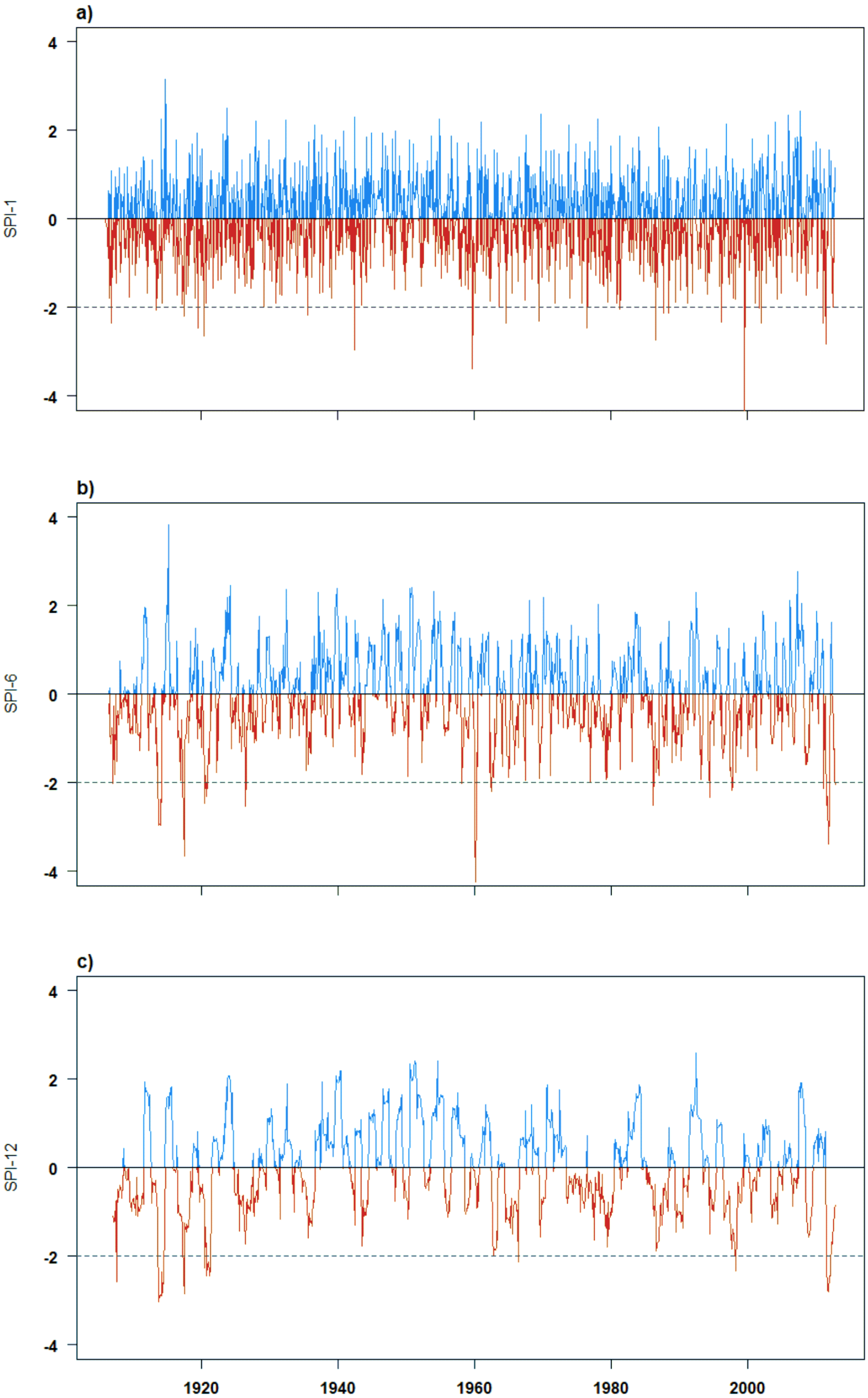

Figure 5. Standard Precipitation Index from 1906 to 2015, with wetter (blue) and drier (red) than normal conditions indicated for a): SPI-1; b) SPI-6; and, c) SPI-12

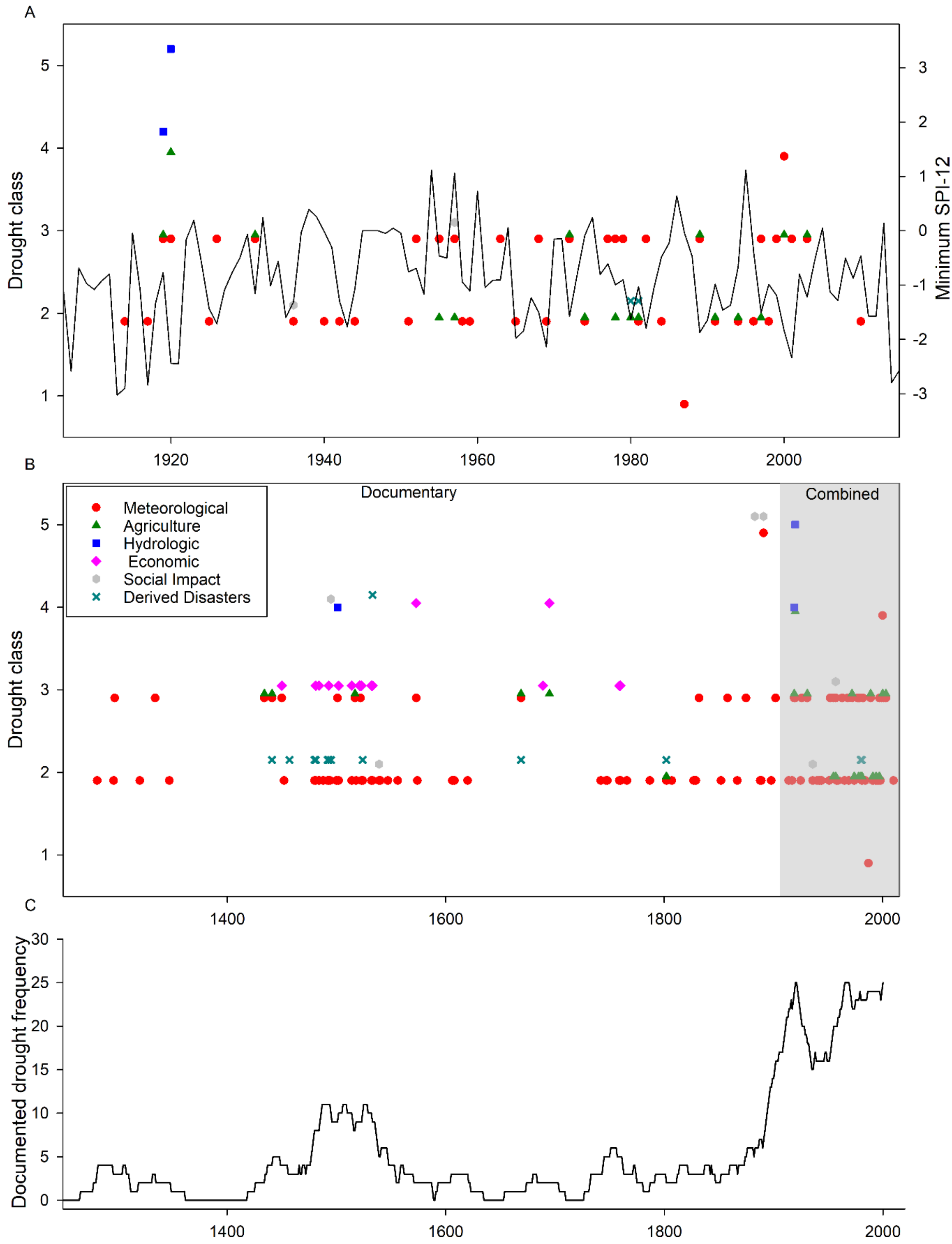

Figure 6. Shenyang drought classification (colour/shape) for a) combined archival and instrumental period (1906-2015) with minimum annual SPI-12; b) augmented period (1200-2015); and, c) a running 30-year mean drought frequency (1200-2015).