Long-term Drought Reconstruction for Beijing since the Ming Dynasty (1368 - 2019)

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Abstract

A greater appreciation of historical sources documenting the weather has been achieved during recent decades, recognising their value in understanding and interpreting long-term climate change, their application and utility for improving climate models and the opportunities they offer for a deeper consideration of societal responses to past climatic events. Using a variety of historical archives, the drought history of Beijing is extended back to 1368, and a new reconstructed instrumental monthly precipitation series presented from 1724-present (2019). This combined instrumental and documentary analysis permits an opportunity to explore past droughts and the inter-relationships between physical, social, and cultural drought impacts. The Standardised Precipitation Index (1724-2019) is augmented with a long-term historical drought classification (1368-2000) based on drought impacts (using a 5-class drought index). Long precipitation reconstruction enables both short- (monthly) and long-term (decadal) drought variability to be robustly assessed for Beijing since the Ming Dynasty, identifying a series of historically severe droughts of comparable severity to recent events, but with a range of varying social and cultural impacts.

Key Words: Historic drought classification, drought reconstruction, documentary sources, wavelet analysis, Beijing, China.

1 Introduction

Drought is a major global challenge, causing more deaths since the start of the twentieth century than any other natural disaster (Delbiso et al. 2017; EM-DAT 2019). No single universal definition of drought exists, with many definitions focused on a deficiency of precipitation over a period of time (Wilhite 2000; Lloyd-Hughes 2014). Drought definitions commonly fall into one of five inter-related categories: meteorological, hydrological, agricultural, socio-economic (Wilhite and Glantz 1985; Heim 2002), with groundwater droughts added by Mishra and Singh (2010). Drought onset is often unremarkable, but follows a prolonged period of precipitation deficiency that propagates through the hydrological system (Palmer 1965; Heim 2002; Lanen 2006), with varying drought impacts emerging several weeks to months after drought onset. As such droughts have been characterised as slow developing pervasive environmental disasters that are hard to predict and manage (Dai 2011), causing significant environmental, social and economic impacts (Van Loon et al. 2016). Drought is a natural product of climate variability, with drought severity potentially exacerbated by additional meteorological elements (e.g. temperature, wind, and humidity) (Brázdil et al. 2008). Severe droughts have been a key driver in disaster studies during the twentieth century, e.g. the 1930s USA 'Dust Bowl' (Schubert et al. 2004). Whilst drought and famine have historically been closely connected, it can be challenging to disentangle the roles of climatic drought and social/cultural inequality, with previously well documented examples, such as the Bengal famine of 1943 (Sen 1981) through to the African droughts and associated famines of the 1980s and 1990s (Biong Deng 1999).

Recent studies have started to explore droughts from a historical perspective (Brázdil et al. 2009, 2018a), seeking to understand long-term variability (Vicente-Serrano et al. 2021) and have considered drought impacts experienced from differing perspectives, including impacts on, water resources (Lennard et al. 2015); agriculture (Brázdil et al. 2018b); infrastructure (Harvey-Fishenden et al. 2019); stream and river flows (Zaidman et al. 2010; Barker et al. 2019) and groundwater (Bloomfield and Marchant 2013); with long robust drought chronologies using combinations of archival and instrumental sources from around the globe increasingly recognised as important in understanding long-term variability and severity. However, much of this work has focused on Europe (Wilhelm et al. 2018), with fewer studies elsewhere (Zheng et al. 2006; Tang et al. 2020).

There is a long history of droughts impacting on communities in China, with some of the earliest accounts relating to the period of King Xuan of Zhou (827/25-782 BC), with the *Da Ya*

Yun Han recording the prayer of King Xuan of Zhou to the heavens for rain and the appeasement of 'the legendary demon causing drought' (Classic of Poetry, n.d.). It demonstrates that communities have been aware, curious and fearful of droughts throughout history. Responses historically focused on a perceived need for intervention from a deity to resolve the situation, a typical cultural response in many historical communities to geohazards (Sangster et al. 2018). The *Han Shu* (Hui Di Ji, Vol.2) in 193 BC records "…summer, big drought", providing a description of the season and degree of the drought. A long history of documenting droughts in China exists, with many local or regional compendiums produced, such as the *Yearly Charts of Dryness/Wetness in China for the Last 500-Year Period* (Academy of Meteorological Science, [Chinese] 1981), which lists all historical droughts between 1470-1974, based on local chronicles, disaster records and records from the Forbidden City archives. A number of notable historical droughts in the twentieth century have highlighted the vulnerability of contemporary communities in China to droughts (e.g. Tang et al., 2020), with agricultural sectors still prone to drought impacts (Barker et al. 2020). Past droughts have had far-reaching impacts on society in China; however, an improved understanding of drought risks can be ascertained from historical records, providing a better understanding of current and future drought risk.

This paper explores the history of drought in Beijing (1368-present), it extends monthly instrumental precipitation data back to 1724, which is augmented with archival information back to 1368, providing a ~650-year drought record. This new extended series offers a valuable opportunity to examine the temporal and spatial variability of drought at Beijing, it assesses drought causing climatic conditions and examines the impact of past droughts on society. This will be achieved through four objectives:

i. reconstruction of a monthly precipitation series for Beijing from 1724;
ii. construction of a new documentary drought classification from the archives for the period 1368 to 1949;
iii. reanalysis long-term drought variability using a Standardised Precipitation Index (SPI) and historical drought reconstruction from documentary sources; and,
iv. develop an understanding of past drought disasters and community impacts from historical sources.

2 Data Acquisition

2.1 Documentary data

The earliest records of weather in China can be traced back to the Yin and Shang Dynasties (about 1300 BC- 1046 BC), with records inscribed onto the scapula of tortoise shells or large animal bones (the Oracle Bone Collection); these records recall details of the Shang royal family, but also include ancillary details such as the state of the weather (Wittfogel 1940). After the Western Zhou Dynasty (approximately ~1046-771 BC), the inscription of bronze wares developed, followed by the Spring and Autumn Period (770-476 BC) with the development of iron smelting and ironware becoming important sources for inscriptions (including documents and laws). During the Qin Dynasty (221-207 BC), this included the carving of stone notes (Bavarian and Reiner 2005). Ouyang et al. (1646) *Ji Gu Lu* (Song Dynasty) contains thousands of pieces of metal and stone that provide records from the King Mu of Zhou period (approximately 992-922 BC) to the Sui and Tang Dynasties (581-907 AD), including records of drought. The exact point at which bamboo/wooden slips start to be used is difficult to determine, however known bamboo and wooden slips archives span the four periods of the pre-Qin (2100-221 BC), Qin (221-206 BC), Han (202BC-220 AD), and Three Kingdoms (220-280 AD) dynasties (Tsuen-Hsuin 1962; Venture 2016). After the Eastern Jin Dynasty (317-420 AD) paper became much widely used for records, which is the main source for many of the ancient books (Needham and Tsuen-Hsuin 1985; Zhang 2004b).

These rare and precious original documents were unavailable for direct use in this study as they have limited access; therefore, it was necessary to access published syntheses or compendiums and/or digitised versions of the documents. These published materials are retained by local libraries and archives, and several publications digitized viewable electronically. Whilst it is inevitably that some subjective assessment was made during data processing, great care and attention was given in the original transcription process, as detailed by previous researchers (Academy of Meteorological Science [Chinese] 1981; Zhang and Crowley 1989; Zhang et al. 2013), with published versions now commonly widely used (Wang and Zhang 1988; Wang et al. 2018). Therefore, this research focused on four sources, which have been systematically analysed, these sources are compendiums of collated historical archive sources, which have been reviewed and edited into books. In addition, as materials relating to the Ming dynasty are more limited, an additional supplement of the historical archive *Ming Shi* was considered. The first of the four books assessed is the *A compendium of Chinese meteorological records of the last 3,000 years* (Zhang 2004a) which provides a detailed history of 3000 years of natural disaster records in China, recording more than 13 kinds of physical phenomenon from the 23rd century BC to AD 1911. The second is the *Historical Materials of Drought Archives in the Qing Dynasty* (Tan 2013). This uses memorial records from the Qing dynasty, including historical materials about droughts reported by provinces and cities in the Qing Dynasty (1689 to 1911), detailing information on drought and flood disasters and post-disaster rescue. The third source is the *Beijing records volume 8 – meteorology records* which present meteorological disasters from 177 BC to AD 1995, concentrated on Beijing (Beijing Local History Compilation Committee 1999). The fourth and final source is the *China meteorological disasters ceremony (Beijing volume)* which was produced by the editorial committee of Beijing Meteorological Bureau and records meteorological-related phenology, agriculture, diseases and infestations, people's livelihoods and details of societal response to droughts (Xie 2005). Each of the works has its own focus and written records are extensive.

2.2 Instrumental precipitation data

The earliest precipitation record in China was recorded in the third century BC, the *Shuihudi Qin bamboo texts* law requires all counties to report rainfall, however the reports have been lost. “平地尺为大雪” (English translation: one foot depth of snow is heavy snow) - from the book *Zuo Zhuan*, shows that in the pre-Qin period, using the thickness of the snow on the flat ground to determine the amount of snowfall. There are many words in the poems of the Tang and Song dynasty that describe rainwater in the units *cun,* which are equivalent to 32mm (Ge et al. 2005). The mathematician Qin Jiushao of the Southern Song dynasty devised the Tianchi rain basin, which appears to have been widely distributed by 1247, these instruments or bowls were of known volume with averages calculated from Spring to Autumn (Chu 1918; Di 2008). Although the concept of rainfall has a long history, there were no fixed and reliable systems or instruments for recording of precipitation until the 18th century.

Early records exist from the Imperial Palace in Beijing, these are recorded within the *Yu-Xue-Fen-Cun* (1736-1911, as detailed by Ge et al., 2005) and the *Qing Yu Lu* which were incorporated into the *Climatography of Beijing* (Beijing Meteorological Service Climate Data Centre 1987). This study uses the *Qing Yu Lu* as it contained measurement records of summer (June, July and August) and annual precipitation in Beijing from 1724 to 1984. The difference between the two provides a 9-month precipitation period which typically contains <25% of annual precipitation; Figure 1). The *Yu-Xue-Fen-Cun* documents record infiltration, snow depth, and when precipitation occurred, as such they provide intermittent records, however these have been used to reconstruct ‘summer’ and ‘annual’ precipitation through a coupled archival analysis and field experimentation (Ge et al. 2005). The recovered sequence overlaps with the start of monthly/daily instrumental rainfall recording in Beijing (1841 - present). In 1841, a geomagnetic meteorological station was instigated by the Russian Spiritual Mission (Russian Church) in Beijing (Feklova 2019), this provided the first instrumental monthly precipitation data. Daily precipitation reporting begins in 1951 (GHCN dataset) this represents the start of continuous precipitation recording in the city. Each of the recording periods and overlap periods which are available for calibration of data comparison are presented in Figure 1, for each of the series.

In constructing a continuous monthly dataset for Beijing for 296 years from 1724 to present the reconstructed instrumental monthly precipitation series combines four datasets: The Global Surface Summary of the Day (GSOD, daily 1957-2019; 2020), the Global Historical Climatology Network-Daily Database (GHCN, daily 1951-2019; Menne et al., 2012), the Two Long-Term Instrumental Climatic Data Bases of the People's Republic of China (TLT, monthly 1841-1993; Tao and Kaiser, 1997), and Climatography of Beijing (CoB, summer and annual 1724-1984; Beijing Meteorological Service Climate Data Centre, 1987) (Figure 1).

3 Methods of Drought Reconstruction and Classification

3.1 Drought pattern from instrumental data

Three stages of data analysis are deployed, the first was to ensure data quality control in the reconstructed series the data, with some infilling of gaps required (Figure 2). All instrumental data are organised as monthly, summer, and annual data series, to enable time-sequential homogenization. Second, gaps within the series were reconstructed and infilled using interpolation to supplement monthly instrumental dataset gaps and infilling monthly data back to 1724, using a seasonal to annual scaling relationship. Third, analyse of the drought year using the Standard Precipitation Index (SPI) and wavelet analysis was undertaken, with analysis at a range of temporal scales (SPI- 6, 12, 24, 36, 48, 60, 120), such a range of SPI- temporal ranges permits a variety of potential drought generating mechanisms to be examined.

3.2 Data integration with homogenization

Data quality analysis of the instrumental datasets identified several gaps resulting from changes in reporting time, data presentation and recording type. The raw daily Beijing precipitation data (1957-2019) extracted from the Global Surface Summary of the Day (GSOD, 2020) are quality-controlled pre-release, with a variety of flags with different meanings requiring consideration (Supplementary Material 1); the key classes that required reviewing are *99.99* which represents missing data, and where trace precipitation is calculated as zero. Similarly, the GHCN (1951-2019) database (Menne et al., 2012) has daily rainfall data, however *T* represents trace precipitation and is noted in some months, which was reprocessed as 0 mm, however such conversions risk underrepresenting rainfall, but permits long-term analysis. The TITLC database includes monthly data from 1841-1993, with early data extracted from the archives of the Russian Spiritual Mission, details of station relocations, instrument changes and observation windows are available in Tao and Kaiser (1997 – station number 54511). Several gaps exist which are infilled using either an average of adjacent records or using the difference from the summer/annual record, scaled to the monthly distribution.

Correlation analysis of the four datasets (Figure 2), identify high levels of correlation at the seasonal and annual level, the CoB does not contain monthly instrumental data and therefore are only considered at seasonal and annual timescales, with all datasets demonstrating significant correlations (p-value < 0.001). The high correlations in GSOD and GHCN databases reflects the duplication of datasets. Whilst anomalies in the bivariate scatterplot are identified, the close positive correlation between datasets provides high reliability for time-series homogenization (Figure 2). The TLTIC series has the potential to extend the instrumental GHCN series by a further 110 years at the monthly scale; the overlapping period of GHCN and TLTIC shows good correlation, the monthly average over the overlapping 42 years (1951-1993) differing by <0.01mm. The strong relationship between the recent instrumental and longer instrumental series, provides confidence in the long instrumental series, 1841-2019 (Figure 3a). The reconstructed series (Figure 3a) from 1724 to 2019, contains 1853 months of data and 298 months with either complete or partial gaps that required infilling (14%). The summer months consist of the highest rates of precipitation in Beijing, with the greatest variability between years. A high number of months of data are missing for the period 2013-2019 in the GHCN dataset, which are infilled with data from the GSOD dataset. Several years consist of partial monthly data, 1884, 1886, 1889, 1900, 1903, and 1937, with annual data also available, in these instances the difference between annual and accumulated precipitation data are infilled using the monthly, seasonal, and annual precipitation distribution (Figure 4a-b). An analysis of 30-year average monthly, seasonal, and annual climate through varying temporal windows (1724-

2019 and 1841-2019), at monthly, seasonal, and annual scales are presented in Figure 3b and Figure 4a-b respectively. The comparable monthly and seasonal distributions for the pre-1841 data enhances confidence in the scaling approach applied, as no notable anomalies are identified.

July precipitation is significantly higher than other months (Figure 4a), with summer (JJA) precipitation typically accounting for >75% of annual total precipitation (Figure 4b), with summer prone to unusually high precipitation in individual years (Figure 2b). Precipitation gradually increased from 1724 to 1870, with average monthly July rainfall reaching 320mm in the period of 1871-1900, which was significantly higher (p-value < 0.001) than other 30-year periods, with a subsequent gradually decreased after 1901 (Figure 3b). The 30-year period 1781 - 1810 also identifies a notably high, but not significant, average rainfall (256mm).

A single homogenised monthly instrumental precipitation series is generated from the above sources, based on, and calibrated to the GHCN series, to enable subsequent updating (Figure 3a). This new extended series will subsequently be used to assess drought severity in Beijing.

3.3 Standardised Precipitation Index analysis

Drought indicators have been widely used to study drought severity and are increasingly used to better understand long-term drought variability, with both scPDSI (self-calibrating Palmer Drought Severity Index; Todd et al., 2013) and SPI (Harvey-Fishenden et al. 2019; Tang et al. 2020; Vicente-Serrano et al. 2021) have been used for such approaches, based on the limited required input data (temperature and/or precipitation data alone, respectively). The use of indices permits a long-term analysis of drought and facilitates drought impact analysis. The SPI does not involve precipitation spatial parameters and can therefore be compared between different locations under different climatic conditions. Importantly, SPI can be calculated through multiple time scales, which can analyse and process different drought types. For example, meteorological drought generally corresponds to short timescales 1-2 months, agricultural drought (1-6 months) and hydrological drought and socioeconomic drought can be shown in 12 months or longer (World Meteorological Organization (WMO), 2012 - Standardization Precipitation Index Guide). Based on the advantages of SPI in drought analysis, this paper uses different time scales to analyse and assess the characteristics of Beijing's historic droughts.

3.4 Wavelet analysis

Meteorological time series (precipitation) are affected by a variety of factors, usually presenting a non-stationary sequence, with unobvious trend(s), interannual or seasonal periodicity, and unpredictable mutations or anomalies. Research on non-stationary time series usually requires time information corresponding to a certain frequency band or domain. A Morlet wavelet analysis (Goupillaud et al. 1984) with a time-frequency multi-resolution function is applied, which can reveal a variety of cycles hidden within a time series. Wavelet analysis has been used extensively to examine long term variability within meteorological series (e.g. Camuffo et al., 2013) and in drought analysis (e.g. Maity et al., 2016; Todd et al., 2013), as they eliminate or reduce noise interference within time series, permitting the identification coefficient and fractal dimensions, the monitoring of mutation points and the identification of periodic components at multiple time scales. The complex wavelet transform provides both phase and amplitude information on the time series, with wavelet coefficients obtained from the wavelet transform, and time-frequency variation characteristics analysed by these coefficients. Wavelet variance can be used to determine the relative intensity of the disturbances of different scales in the signal and the main time scales present (Torrence and Compo 1998).

3.5 Drought story from documentary data

In examining the sources, descriptions often detail weather phenomena such as high temperature and little rain, no rain, delayed rain and snow, or the length or degree of drought expressed, such as prolonged drought, frequent droughts, consecutive years of drought. Such information can be converted into drought indices. Documentary drought classifications have been widely applied in drought analysis (see Brázdil et al., 2018a), typically focused on the conversion of documentary data to a numerical indices, often on either a 3, 5 or 7 point scale (Nash et al. 2016). Typically, no description, normal or mundane weather phenomena is grade 1, with subsequent increased grading of severity. Previous studies rarely classify drought or other meteorological parameters at the daily scale, focussing on aggregated periods such as months, seasons, or years, as it can be difficult to determine what is 'normal' weather. This study applies a 5-point drought classification; however, the exact nature of the grading reflects the type of drought being described (meteorological, hydrological (including groundwater), agricultural or socio-economic), recognising the variability associated with drought type within the descriptive accounts, these are presented in Table 1. The reconstructed drought series for Beijing is presented in Figure 3c, spanning 1368-2019.

The majority of documentary accounts detail meteorological and agricultural aspects, with few hydrological drought records, however comments relating to wells, canals, rivers, reservoirs, and other objects are recalled, these though are generally brief and lack detail. In the era of underdeveloped agricultural technology, the growth of crops relies heavily on natural rainfall and can have a direct impact on human mortality and heath, as such these are often well described as they would impact on taxation and is directly related to the state of the communities. Accounts recall a range of impacts from small things such dust covering the fields, to the desperation of no harvest/grain. In this case, the descriptions of seedlings, wheat, rice fields, and agricultural harvests are examples of agricultural drought. Socio-economic drought is a record of the impact of drought on society from social stability, business activities, and policies. The specific evaluation criteria, drought types and corresponding grade records can be seen in Table 1; with changing distributions of impacts and types of drought noted varying through time, in part reflecting social and cultural resilience tools.

4 Results and Discussion

4.1 Pre-instrumental period drought

From 1368 to 2000 AD nearly 60% of the years include some form of record of drought in the Beijing area. The textual data records drought in 58.8% of the years 1368-1644 (Ming Dynasty); 61.8% during 1645-1911 (Qing Dynasty); 48.6% in 1912-1948 (the Republic of China) and 55.8% during 1949-2000 (modern); indicating comparable accounting through the overall time-period of consideration in this study. The impact of accounts detailing drought are important in assessing historical drought impacts. The accounts can be considered as providing either explicit or implicit descriptions of drought, for example implicit drought may reflect a description of a socio-economic impact without an account of meteorological drought. Within this study only those accounts providing explicit statements or accounts of drought impacts are used. For example, there was no historical record of a meteorological drought in the ten years before 1421, however the account for that year:

“水旱相仍，民剥树皮为食。卖妻鬻子，夺民食。”

(“Floods and droughts had a huge impact, and people deprived used bark as food. Selling wives and children, robbing each other of food”)

Such an account provides a clear indication of a meteorological (class 4) drought, but with socio-economic impacts of class 5 (selling of family). Similarly, accounts in the years 1516, 1523, 1601, 1640-41 and 1832 detail meteorological drought accompanied by severe agricultural and socio-economic droughts. In 1944, this is supplemented with detailed information/statistics, "the death toll was 2544 due to famine."

In total class 5 [frequency of class 4 droughts] droughts are recorded in three [22] years for meteorological (1473, 1601, 1999); three [17] years for hydrological droughts (1976, 1981 and 1999); 17 [15] years for agricultural (1458; 1459; 1468; 1473; 1516; 1523; 1560; 1573; 1581; 1582; 1586; 1601; 1620; 1630; 1631; 1640; 1832) and eight [33] years for socio-economic (1421; 1516; 1523; 1601; 1641; 1832; 1944). The higher propensity for records to recall extreme/severe agricultural and socio-economic drought impacts are in part likely to be a function of the materials reviewed, with many archival sources often focused on legal and taxation aspects. The focus on agriculture also reflects the higher vulnerabilities of society to poor harvest. The temporal variability is interesting, with class 5 hydrological drought impacts only documented from the last 50 years, potentially reflecting greater awareness or stresses on water supplies. Temporal consideration of the class 4 and 5 hydrological records is notable in that they predominantly cover two periods 1464-1689 and 1975-2019.

The significance of droughts in Chinese history is considerable, with the collapse of the Ming Dynasty (1644) attributed to the extreme drought of 1637-1643 (Cook et al., 2010; Zheng et al., 2014), or also called the ‘late Ming megadrought’ (Chen et al., 2020). Within the drought chronology presented, extreme droughts (class 5) are identified within the Beijing series for both agricultural (1640) and socio-economic drought classifications (1640 and 1641), however neither meteorological or hydrological classifications record a drought of class 4 or 5. The lack of extreme/severe meteorological or hydrological drought in those years, class 2 or 3 meteorological droughts are recorded in each year (no hydrological drought records recorded), would suggest that this was a pervasive drought event spanning several years with the greatest impacts felt in the agricultural and societal classes. This coincided with a deteriorating political and fiscal environment in the late Ming period, with the societal implications of the drought exacerbated by reduced social and cultural resilience (Peng et al.

2014; Chen et al. 2020). In considering the archival record it is reassuring to see other documented droughts are also evident, such as 1586-89; Shen et al. (2007) noted it was a particularly severe drought over eastern China, with accounts detailing “no water flows in rivers” and “springs dried up”, with class 4 and 5 droughts also documented in both agricultural and hydrological series. The more recent drought of 1959-62, is also evident and has been extensively documented previously (e.g. Ashton et al., 1984), with five class 4 or 5 drought impacts recorded (meteorological, agricultural and socio-economic – Figure 3c).

A number of years are identified that are less well documented as suffering extreme/severe droughts (Figure 3c), but contain at least two different impacts at class 4 or 5, such as 1421 and 1560-61 (meteorological, agricultural and socio-economic), and the periods 1468-73 (7 impacts); 1516-1524 (8 impacts) and 1573-1621 (23 impacts). Both 1516-1524 and 1573-1621 overlap with longer drought periods identified by Hao et al. (2020) for eastern China, whilst Zhang (2005) identifies the drought of 1585-90 as particularly severe. Consideration of classes 4 and 5 together reduces the risk of miss-classification, and likelihood of capturing the range of severest drought impacting events. Comparison of these periods to proxy climate series identify a number of corroborative accounts, the periods 1560-61 and 1580s both identified by Yi et al. (2012) as having strong negative summer precipitation anomalies for north-central China.

Consideration of the drought chronology (Figure 3c) identified that the period 1650-1865 appears to be drought poor, Yi et al. (2012) also identifies a comparable period (1650-1850) as generally wetter with few severe negative precipitation anomalies, exceptions being 1721-2 and 1792. Consideration of the drought chronology presented here identifies a class 4 agricultural drought in 1721, with class 3 meteorological and socio-economic impacts also recorded, with class 3 impacts also recorded for 1792. The class 4 impacts identified for 1832 (meteorological, agricultural and socio-economic) are also identified by Wan et al. (2016) when assessing droughts from 1689-1911, they also note that the severe droughts during 1876-80 are not as significant in Beijing as other regions of China (Tang et al. 2020), which supports our findings (only two accounts of class 4 drought in this period).

In considering the nature and types of droughts recorded within the chronology a clear preference towards agricultural and socio-economic drought during the historical period is identified, with greater prevalence of hydrological and meteorological droughts during the instrumental period. Inevitably socio-economic drought is resultant of the other three forms of drought, but is also impacted by the social capacity to mitigate the worst impacts of the drought, whether through reduced vulnerability and improved socio-economic resilience, with breakdowns in social order historically associated with the worst droughts (Pierre-Etienne (Translated by Elborg Foster), 1990). The socio-economic factors responsible for social breakdown which led to looting and riots was often cited as famine, resulting from unbalanced food distribution; unsound legal systems or inadequate economic regulation, which caused food prices to surge, with resulting personal responses ranging from praying to deities, selling family members and migration. However, in assessing the nature of such responses considerable care is required, with sensitivity to who is recording and potential biases and interests within such accounts.

It is notable that the reduced frequency of droughts from ~1650 coincides with societal improvements, as Shiue (2005) identifies that the Kangxi emperor (1662-1722) significantly expanded the system of state granaries with a focus on forestalling future food crises. In considering the nature of the records used within this study there is an inevitably focus on agricultural and socio-economic drought, as many of the records consulted address taxation at local and regional levels. In examining such records there is inevitably a bias to events that reduce taxation, and droughts are a frequent cause. By the reign of Emperor Yongzheng (1722-1735) relief systems were being initiated during famines with resources distributed to mitigate the severest impacts, coinciding with a programme of widespread agricultural expansion with infrastructure improvements (e.g. irrigation canals) to support agriculture (Perdue 2004). Therefore, the period from ~1650 may be one of reduced droughts, or at least reduced vulnerability to agricultural drought consequences, as food supply and prices stabilised; an argument supported by Pierre-Etienne (1990) and Wong (1982), as they state the granary system probably reached its maximum extent in the eighteenth century and helped overcome the worst of the famine of 1743-4 (class 3 meteorological, agricultural and socio-economic drought). To better understand whether the apparent reduced incidence of drought is a function of changing climatic conditions or reduced societal vulnerability we can examine the long instrumental precipitation record available within Beijing (1724-present).

4.2 Instrumental reconstruction (1724-2019)

The summer and annual precipitation data (1724-1841) fit to the monthly distribution (Figure 4a) provides a precipitation series from which an extended SPI is generated. Analysis of the 30-year precipitation characteristics identifies that whilst the early data 1724-50 has a low mean and quartiles (Figure 3b), it is not unusual against the longer series, nor do monthly totals appear unusual (Figure 4a), however the absence of comparable precipitation series means comparison to other datasets are not possible. Analysis of the 30-year seasonal pattern (Figure 4b) suggests that comparable seasonal totals are achieved through the pre- and post-1841 periods, with the most recent 30-year period (1991-2019), presenting comparable annual and seasonal totals to the earliest period (1724-1750).

Over 75% of annual precipitation falls within the summer months, with considerable inter-annular variability, with summer precipitation ranging from 141 (1999) to 1385 (1891) mm during the period 1724-2019. Percentile representation of summer precipitation anomaly highlights the importance in drought formation/severity, with well documented extreme/severe droughts over the last 30-years evident (Figure 5a), coincident with a weaking monsoon (Wang and Chen 2010). The previously identified drought poor period is also apparent from the 1770s-1850s in Figure 5a, with few multi-year droughts. Inevitably with such a strong seasonal skew to precipitation to the summer months, low summer precipitation can have important implications on drought development. The precipitation anomalies identified at the seasonal scale are also evident within the monthly data (Supplementary Material 2). Seasonal anomalies are identifiable in a number of years, but demonstrate that whilst extremes occur, it is high precipitation that can be particularly anomalous (Figure 5b), a phenomenon related to strong monsoon seasons in the Beijing and east Asian Summer Monsoon (EASM) region (Yihui and Chan 2005), which have been linked to larger climatic processes such as ENSO (Nino3 SSTA), however these relationships are considered as temporally unstable (Huijun 2002; Yu et al. 2021).

4.3 SPI analysis and temporal variability of droughts, 1724-2019

A range of temporal SPI periods are considered, from 6 months (SPI-6) to 10 years (SPI120), for both the temporal windows 1724-2019 and 1841-2019. SPI-6, -12, -24 and -60 are presented in Figure 6a-d. Shorter SPI provide a better depiction of seasonal and annual drought conditions, whereas longer SPI (SPI-24, -36, -48) permit an analysis of multi-annular droughts; SPI-60 and -120 are also considered, which potentially permit a better depiction of longer-underlying changes in climatic systems. The variation in SPI values pre- and post-1841 demonstrates that scaling reduces the sensitivity of the monthly signal (Figure 6a), however consideration of the SPI-12 for 1724-2019 suggests a comparable range of SPI values (Figure 6b), with a prolonged dry phase 1730-1770, which contains few extreme droughts (SPI <-2) identified. It was notable within the documentary analysis that this appears as a drought poor period, except for sporadic years such as 1743-44. However, as previously noted this may reflect greater social and community resilience rather than a more favourable climate, as is suggested from the instrumental data. The period 1770-1865 appears to be generally wetter, which coincides with a period previously identified as drought poor within the documentary accounts (Figure 3c). The drought of 1869 is evident within all four SPI plots presented (Figure 6a-d), but is not recorded within the documentary accounts as severe (class 2). In contrast the extreme agricultural and socio-economic and severe meteorological drought of 1832 is not particularly notable in any of the SPI plots. From the 1890s the frequency of severe SPI droughts appears to increase (SPI-12), with several severe droughts (1900, 1920-22, 1942-43; 1945; 1965-66; 1968; 1981; 1999-2001; 2006). At SPI-24 the most severe drought is that of 1920-22, however at SPI-60 the severest is 1999-2001 (Figure 6d). Within the 296-year drought history presented, the severest droughts at most SPI temporal scales are those of 1740s and the millennium drought (1999-2001).

The SPI series shows marked changes in pattern with high amplitude variations between dry/wet conditions during the 1890s, with more subdued higher frequency oscillations during the 1990s. Continuous Morlet wavelet transforms are calculated based on Torrence and Compo (1998) for the monthly SPI data; with concentrations of power identified (Figure 6 – bold contours). SPI-6, -12, -24 and -60 timescales (1724-2019) are presented with the wavelet analysis used to reveal periodic evolution of droughts, which have in Beijing been associated with the EASM, and may therefore reflect comparable cyclicity in the EASM. Inclusion of the extended timeframe (1724-1840) reduces the strength of the relationship in the longer series, resulting in the loss of significance at the SPI-6 wavelet power spectrum of the ~8-year cycle. At SPI-6, -12, -24 and -60 the wavelet power spectrum expresses itself as significant above the ~16-year periodicity.

Statistical analysis of SPI-6, -12, or -24 all fail to identify any significant relationships with EASM over the period 1851-2019. Analysis of drought rich periods identified in this study compare favourably with Yamada et al's. (2019) reconstructed EASM series, with the period 1450-1650 identified as one of enhanced EASM. The recent period is identified by Li et al. (2017) as one of a weakening EASM from the 1880s, which intensified after the early 1990s, however this later phases appears to coincide with increased droughts. The weakening since 1880 in EASM may be reflected by a slight (insignificant) decline in precipitation since ~1880 (Figure 3a), with increasing temperatures (Zhang et al. 2017), but is not reflected over the longer timeframe presented here (1724-2019).

5 Conclusions

This study has presented a new Beijing drought series reconstructed using a combination of historical archives and instrumental data, including a new scaled precipitation series extension coupled to an extended drought impact classification (1-5) series using four drought types: meteorological, hydrological, agricultural, and socio-economic. During the historical period (1368-1724) several severe and extreme droughts are identified, with a clear indication that severe/extreme droughts where more common during the period 1450-1650 and appear to have increased in frequency over the last 50 years. The period 1650-1850 appears to be one of few droughts and may be considered as drought poor in Beijing, with increased droughts in recent years.

The manifestation of the drought classes considered has changed, from increased prevalence of early agricultural and socio-economic droughts, through to hydrological drought being more evident during the last 50 years. This change likely reflects increased awareness of hydrological responses, but may also suggest greater pressures on local/regional water systems, as new technologies and infrastructure reduce the risk presented to agriculture and communities and societies. The scaled summer-annual data to monthly resolution presents comparable results to the monthly/seasonal scales (Figures 4a, 4b, 5b; SM2), which when used within the SPI reduces any risk of error/poor fitting, particularly at >SPI-12; with the most severe extreme droughts identified in the period c.1750 and 1999, supported by archival accounts (Figures 3c, 5a).

This study demonstrates that droughts are a recurring characteristic of the climate of Beijing, however the nature of their impact has changed over the study period (1368-2019). The potential mechanisms that generated severe/extreme droughts in the sixteenth and seventeenth century and millennium drought may differ. A weaking of the EASM over the last century suggests continued analysis of the mechanisms responsible for drought in Beijing requires further consideration, as they appear complex and varied through time.

6 Data availability

A. GSOD: Global Surface Summary of the Day, 2020, electronic dataset, National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce, <https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00516#>
B. CHCN: Menne, Matthew J., Imke Durre, Bryant Korzeniewski, Shelley McNeal, Kristy Thomas, Xungang Yin, Steven Anthony, Ron Ray, Russell S. Vose, Byron E. Gleason, and Tamara G. Houston (2012): Global Historical Climatology Network - Daily (GHCN-Daily), Version 3. NOAA National Climatic Data Center. doi:10.7289/V5D21VHZ [March 2020].
C. TLTIC: Tao Shiyan, Fu Congbin, Zeng Zhaomei, and Zhang Qingyun. 1997. *Two Long-Term Instrumental Climatic Data Bases of the People's Republic of China.* ORNL/CDIAC-102, NDP-039. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/cli.ndp039. https://cdiac.ess-dive.lbl.gov/epubs/ndp/ndp039/ndp039.html
D. COB: Beijing Meteorological Service Climate Data Centre 1987, *Climatography of Beijing*, Beijing Publishing, Beijing.

7 Funding

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8 Materials Availability

Digital material availability is identified above (Data availability), specific archival materials are listed beneath the references, whilst all other sources of historical data are cited. Additional information is included within the main body of the paper (section 2 Data Acquisition).

9 Code Availability

All R-code used is stated within the paper and freely available via R packages.

10 Author contributions

LT undertook data collection, analysis, writing of the paper, figure development
HS undertook data analysis, writing and editing
NM undertook project conception, data analysis, writing and editing,

11 Declarations (ethics)

No conflicts of interest exist

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Book of Han (Han Shu. 汉书)

History of Ming (Ming Shi. 明史)

Shuihudi Qin bamboo texts (Shui Hu Di Qin Jian. 睡虎地秦简)

Zuo Zhuan: Yin Gong – ninth year of Yin Gong (Chun Qiu Zuo Zhuan: Yin Gong - Yin Gong Jiu Nian. 春秋左传·隐公·隐公九年)

Table 1. Example descriptors for the qualitative drought classification

	Grade 1 *Light*	Grade 2 *Mild*	Grade 3 *Moderate*	Grade 4 *Severe*	Grade 5 *Extreme*
Meteorological	Monthly rainfall below normal; No rain for days; Rain delayed; High temperature; Windy/Haze/ Yellow dust.	Drought in spring, autumn, or winter; Small range drought; Sand blown by the wind; Winter, no snow.	Summer drought; No rain in two seasons or more; Wide ranging drought; Prolonged drought; Drought deviant; Frequent drought	Less rain for more than half year Heavy/Extreme drought	Years of heavy drought disaster Lasting less rain for one year or longer
Hydrological	Involved hydrology but not many details.	Soil is dry; Less water; lots of silt in river.	Product well for irrigation Land desolation well dry up	Canal dry up Land salinization River dry up	River dry up for several months Land desolation widely People death due to water shortage
Agricultural	Dust cover crop Wheat a bit dry Soil dry Looking forward to wet/rain	Wheat harvest slightly reduced Difficult farming Farming period delay	Injury crop field Wheat wither No seeding Grass/tree scorched Rarely harvest Wilderness fields Locust eat crop	Plants have almost death Difficult farming (harvest higher than 50%)	Years of drought and flood Locust eat most of the crop No harvest/ Wheat all withers for season or longer Difficult farming (harvest lower than 50%)
Socio-economic	Theft	People living hard/ in poverty Ship passenger scarce Unemployment	Displaced Famine/ lack of food Tax delay/ free in a year Half of the land rent loan seed to plant A substantial number of beggars Snatch supplies/ food	Thousands of victims/ displaced/ heavy famines Plague epidemic Death Rice price raise extremely fast People cannot survive Tax free more than one year	Millions of victims/ displaced/famine s Lots of death or more than thousands of people death Cannibalism Selling wife and son

Figures

Figure 1: Sources of rainfall data used in the construction of the composite rainfall record for Beijing for 1724-2019. Rectangular boxes show all years of available data, with black areas showing years used to construct the rainfall record. The red areas in the composite series indicate where summer/annual data is fit to generate monthly totals.

Figure 2: Correlations of datasets GSOD(A), CHCN(B), TLT(C) and COB(D) for (a) monthly, (b) summer and (c) annual timescales. *** denotes significance level of <0.001

Figure 3: a) Reconstructed monthly/annual precipitation series for Beijing 1724-2019; b) annual variability in precipitation over 30-year blocks; c) Drought impact classification, 1368-2019

Figure 4: a) 30-year monthly precipitation total (1724-2019); b) 30-year seasonal precipitation totals (1724-2019). Note: the first period is 26 years rather than 30 years (1724-1750).

Figure 5: a) percentile summer precipitation anomaly; b) Seasonal precipitation anomalies, 1724-2019

Figure 6: SPI-6/12/24/60 (a-d respectively) Standard Precipitation Index, wavelet power spectrum, and global wavelet spectrum in different SPI time scale.

Supplementary materials

Supplementary Material 1: Precipitation flag explanation and approach method

Flag	Meaning	Approach
A	1 report of 6-hour precipitation amount	*4
B	Summation of 2 reports of 6-hour precipitation amount	*2
C	Summation of 3 reports of 6-hour precipitation amount	*4/3
D	Summation of 4 reports of 6-hour precipitation amount	*1
E	1 report of 12-hour precipitation amount	*2
F	Summation of 2 reports of 12-hour precipitation amount	*1
G	1 report of 24-hour precipitation amount	*1
H	Station reported '0' as the amount for the day (e.g., from 6-hour reports), but also reported at least one occurrence of precipitation in hourly observations--this could indicate a trace occurred, but should be considered as incomplete data for the day	Trace (0)
I	Station did not report any precipitation data for the day and did not report any occurrences of precipitation in its hourly observations	0

Supplementary Material 2: Monthly precipitation anomaly (January to December), 1724-2019.

Figures

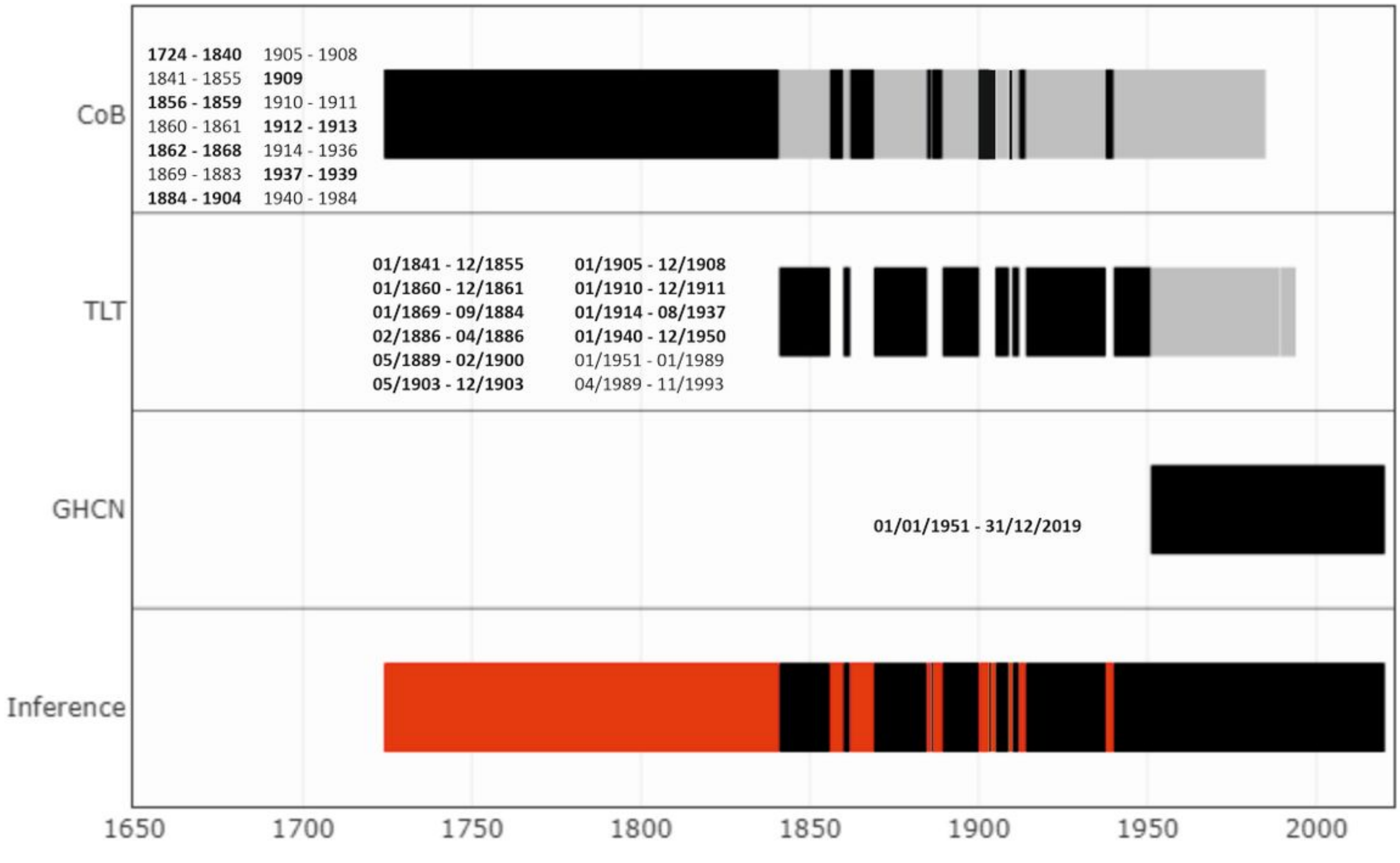

Figure 1

Sources of rainfall data used in the construction of the composite rainfall record for Beijing for 1724-2019. Rectangular boxes show all years of available data, with black areas showing years used to construct the rainfall record. The red areas in the composite series indicate where summer/annual data is fit to generate monthly totals.

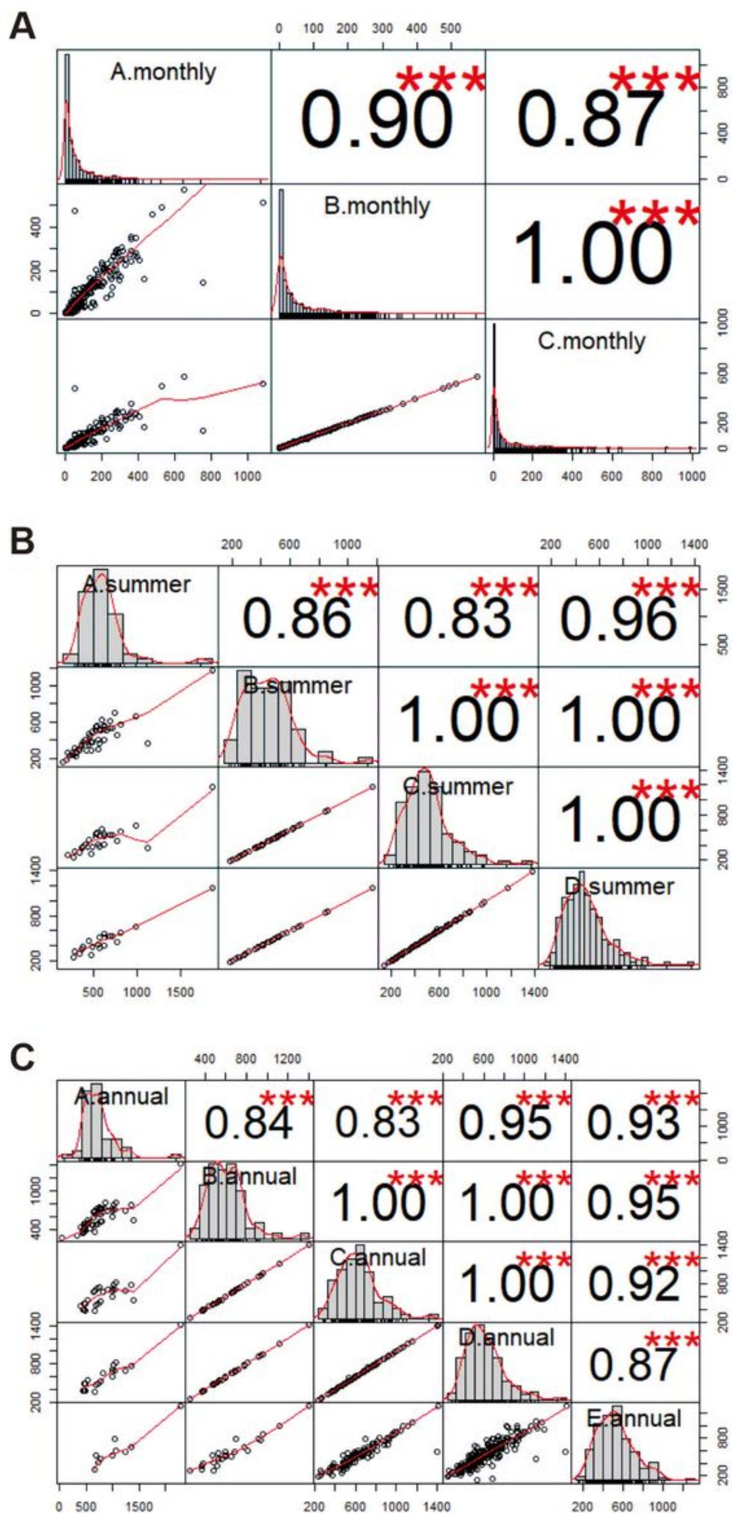

Figure 2

Correlations of datasets GSOD(A), CHCN(B), TLT(C) and COB(D) for (a) monthly, (b) summer and (c) annual timescales. *** denotes significance level of <0.001

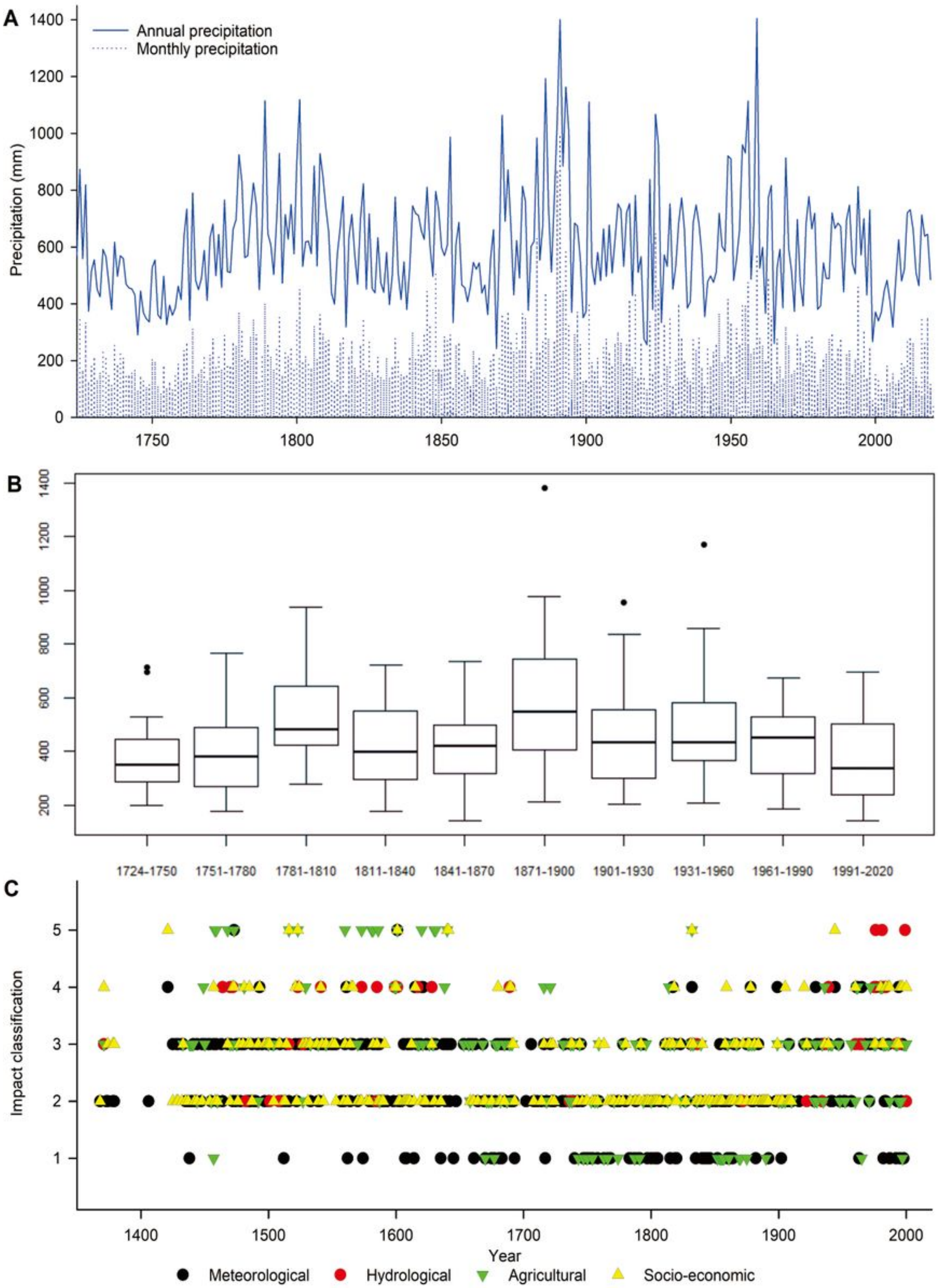

Figure 3

a) Reconstructed monthly/annual precipitation series for Beijing 1724-2019; b) annual variability in precipitation over 30-year blocks; c) Drought impact classification, 1368- 2019

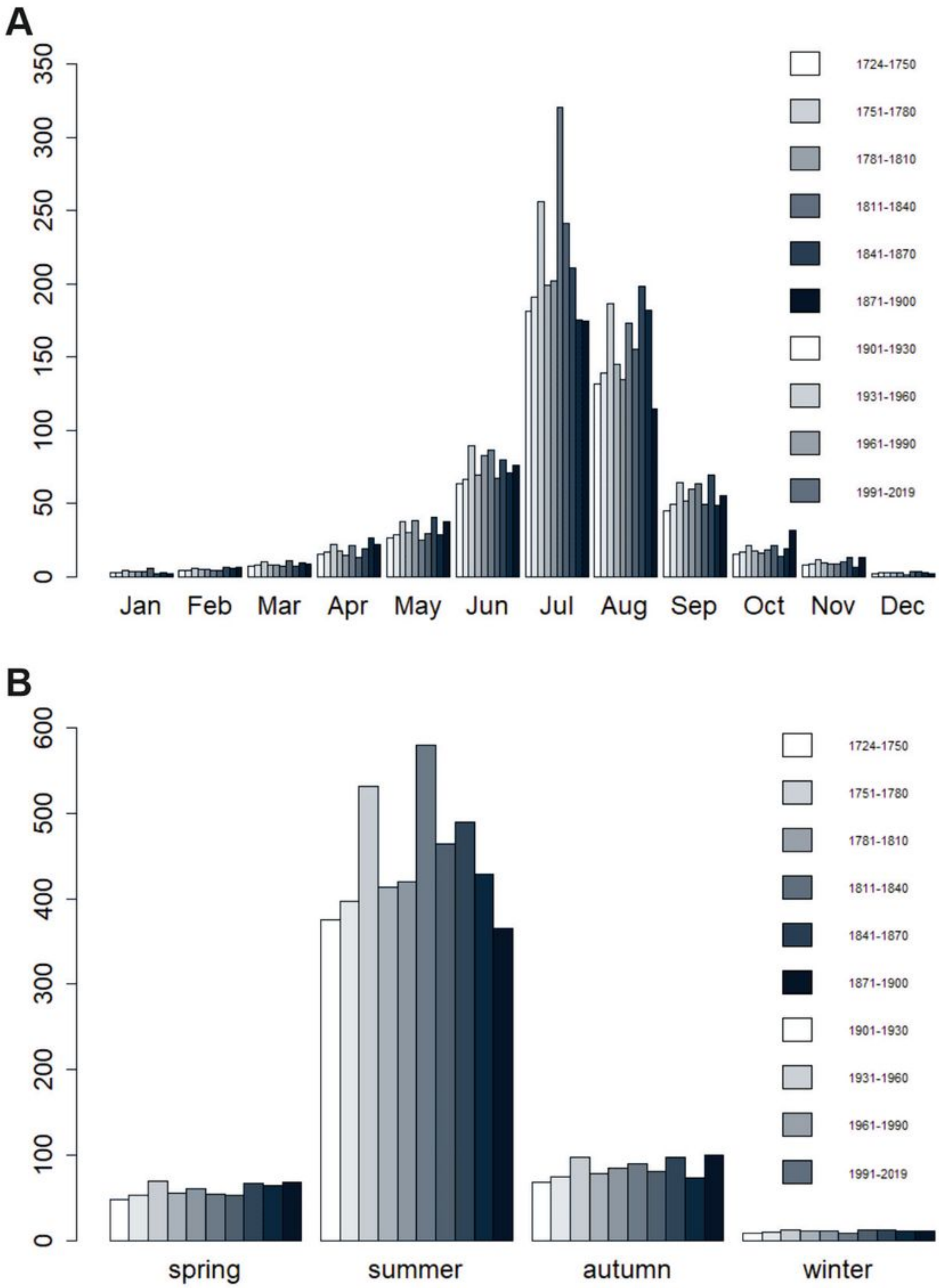

Figure 4

a) 30-year monthly precipitation total (1724-2019); b) 30-year seasonal precipitation totals (1724-2019). Note: the first period is 26 years rather than 30 years (1724-1750).

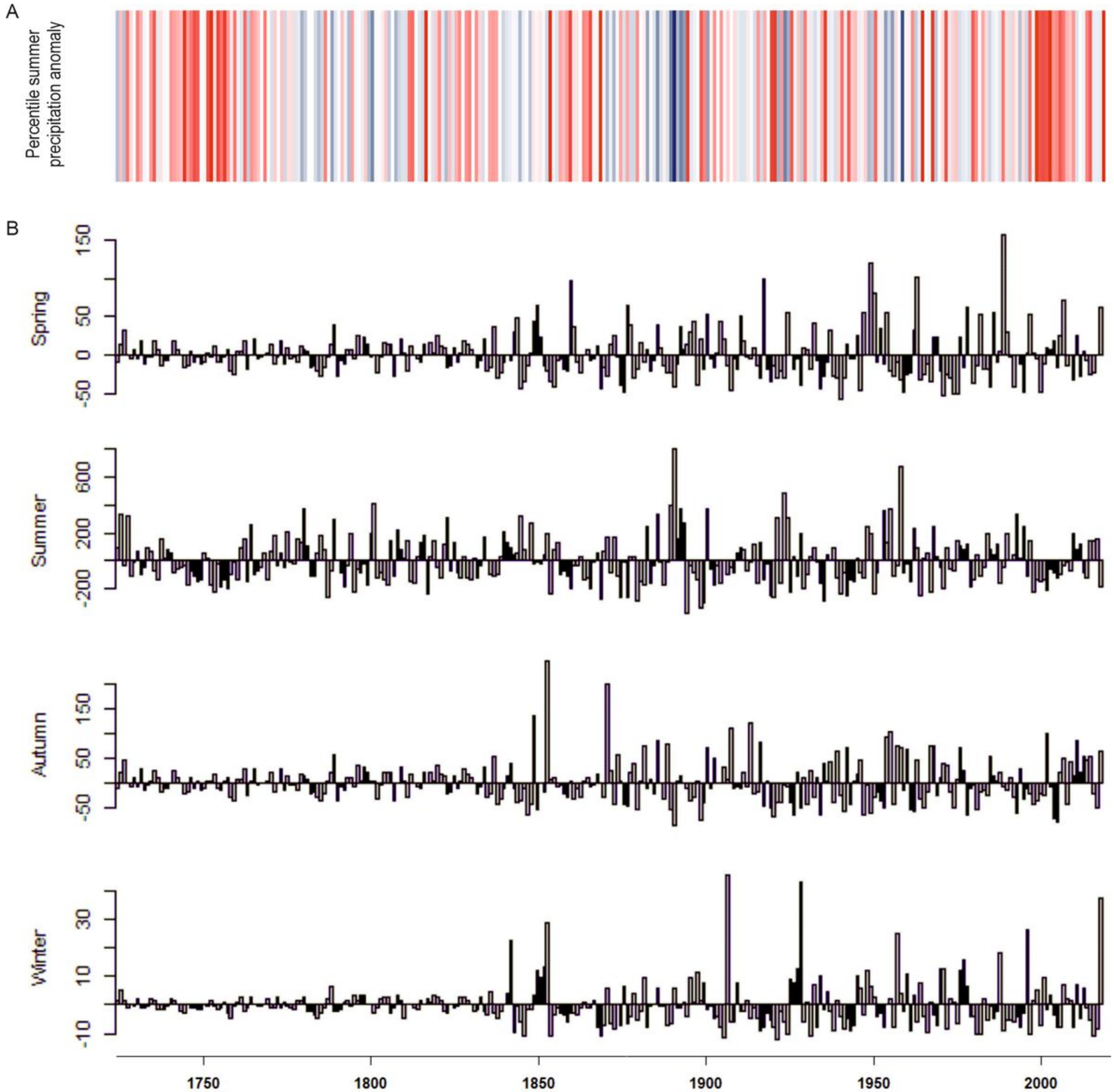

Figure 5

a) percentile summer precipitation anomaly; b) Seasonal precipitation anomalies, 1724-2019

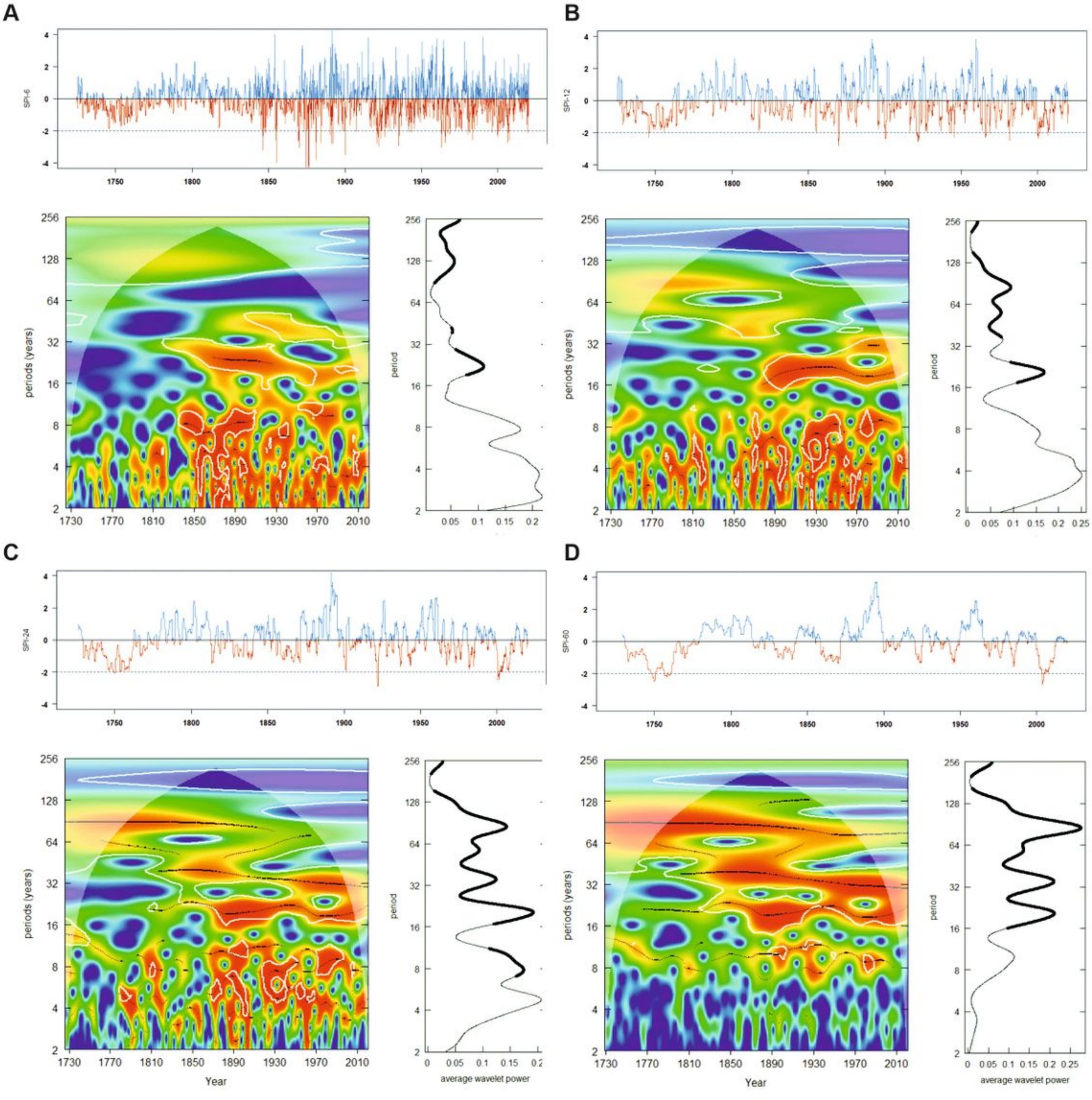

Figure 6

SPI-6/12/24/60 (a-d respectively) Standard Precipitation Index, wavelet power spectrum, and global wavelet spectrum in different SPI time scale

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SM2.jpg