Spatial-temporal variation and impacts of drought in Xinjiang (Northwest China) during 1961-2015

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Observations indicate that temperature and precipitation patterns changed dramatically in Xinjiang, northwestern China, between 1961 and 2015. Dramatic changes in climatic conditions can bring about adverse effects. Specifically, meteorological drought severity based on the standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) showed a decreasing trend in Xinjiang prior to 1997, after which the trend reversed. SPEI-based drought severity shows a much stronger change during 1997-2015 than the SPI, which is independent of the effect of evaporative demand. Meteorological drought severity has been aggravated by a significant rise in temperature (1.1°C) over the last two decades that has not been accompanied by a corresponding increase in precipitation. As a result, the evaporative demand in Xinjiang has risen. An examination of a large spatio-temporal extent has made the aggravated drought conditions more evident. Our results indicate that increased meteorological drought severity has had a direct effect on the normalized difference vegetation index (NDVI) and river discharge. The NDVI exhibited a significant decrease during the period 1998–2013 compared to 1982–1997, a decrease that was found to be caused by increased soil moisture loss. A positive relationship was recorded between evaporative demand and the runoff coefficients of the 68 inland river catchments in northwestern China. In the future, meteorological drought severity will likely increase in arid and semiarid regions as global warming continues.

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ABSTRACT

Observations indicate that temperature and precipitation patterns changed dramatically in Xinjiang, northwestern China, between 1961 and 2015. Dramatic changes in climatic conditions can bring about adverse effects. Specifically, meteorological drought severity based on the standardized precipitation index (SPI) and the standardized precipitation evapotranspiration index (SPEI) showed a decreasing trend in Xinjiang prior to 1997, after which the trend reversed. SPEI-based drought severity shows a much stronger change during 1997-2015 than the SPI, which is independent of the effect of evaporative demand. Meteorological drought severity has been aggravated by a significant rise in temperature (1.1°C) over the last two decades that has not been accompanied by a corresponding increase in precipitation. As a result, the evaporative demand in Xinjiang has risen. An examination of a large spatio-temporal extent has made the aggravated drought conditions more evident. Our results indicate that increased meteorological drought severity has had a direct effect on the normalized difference vegetation index (NDVI) and river discharge. The NDVI exhibited a significant decrease during the period 1998–2013 compared to 1982–1997, a decrease that was found to be caused by increased soil moisture loss. A positive relationship was recorded between evaporative demand and the runoff coefficients of the 68 inland river catchments in northwestern China. In the future, meteorological drought severity will likely increase in arid and semiarid regions as global warming continues.

INTRODUCTION

Severe droughts have occurred more frequently as a result of recent warming, especially in Africa and Asia (*Li et al., 2015; Dai, 2011; Zhang and Zhou, 2015*). Drought is the most damaging, widespread, and urgent natural disaster, with negative impacts on agriculture, ecosystems, hydrology, economic and social activities, and environmental health (*Vicente-Serrano et al., 2010; Wang et al., 2011; Yu et al., 2013; Liu and Jiang, 2014; Chen and Sun, 2015*). Droughts are often grouped into four types: meteorological, hydrological, agricultural, and socioeconomic (*Council, 2004; Benitez and Domecq, 2014; Mishra and Singh, 2014*). Meteorological drought precedes and induces other types of droughts, and local feedbacks often enhance atmospheric anomalies (*Trenberth et al., 1988; Dai, 2011; Potop et al., 2014; Li et al., 2015*). A better understanding of drought is therefore of primary importance in order to enable early warnings of threats to environmental resources.

East Asia, which is dominated by the Pacific-Japan and Silk Road long-distance connection patterns (*Zhang and Zhou, 2015*), is highly influenced by drought. China is mainly located in East Asia and is strongly impacted by drought (*Zhang and Zhou, 2015; Li et al., 2015*). Drought severity has increased significantly in the past half-century, causing substantial damage (*Xu et al., 2015; Wang et al., 2012*). Both *Zhang and Zhou (2015)* and *Yu et al. (2014)* report that severe drought has become more frequent since the late 1990s all over China, with particularly strong increases in southwestern and northern China (*Wu et al., 2011; Yang et al., 2013*). Encouragingly, however, drought severity has decreased in Xinjiang and on the Tibetan Plateau (*Wang et al., 2011; Zhang et al., 2012*), and the drought situation in the Huang-Huai-Hai Plain of China has remained stable for the past 30 years (*Wang et al. 2015*). *Xu et al. (2014)* presented the spatio-temporal variation of drought in China based on the 3-dimensional clustering method.

49   In arid regions, widespread drying is common because precipitation depends strongly on a

50   few precipitation events; if these events do not occur, the region becomes increasingly dry (*Dai,*

51   *2011; Sun et al., 2006; Li et al., 2017*). *Meza (2014)* reported significantly increased drought

52   trends based on SPEI values over northern and central Chile (one of the driest regions in the arid

53   Americas). In East Asia, most drought studies have concentrated on the eastern monsoon region

54   although arid regions in China have sustained severe and costly droughts in the past few decades

55   (*Wang et al., 2015*). For example, eastern arid China suffered a severe drought from 1994 to

56   1995 that caused a 32% decrease in summer grain production (*Zhang and Fang, 1995*). In

57   northwestern China, drought-affected and drought-damaged area has increased over the past two

58   decades, and the annual damaged area reached 0.36×10^7 ha in the 1990s (*Wang et al., 2015*).

59   *Zhang et al. (2012)* found that droughts in Xinjiang have weakened, but that the change

60   properties are different in different regions of Xinjiang. Using precipitation-based drought

61   indices, *Li et al. (2016)* also indicated that drought severity has decreased. *Tao et al. (2013)*

62   indicated that the frequency of moderate and severe droughts has decreased in the Tarim River

63   basin, Xinjiang, but that extreme drought became slightly more prevalent after 1986. *Zhang et al.*

64   *(2015)* assessed the vulnerability of the Tarim River basin to drought and found that drought

65   dynamics can vary within a larger region and among indices.

66   Various indices have been developed to depict and monitor drought events more effectively.

67   For example, the standardized precipitation index (SPI; World Meteorological Organization

68   (WMO), 2012) and the Palmer drought severity index (PDSI; Palmer, 1965) have been widely

69   used in the meteorological community to monitor drought severity (*Palmer, 1965; McKee et al.,*

70   *1993; Vicente-Serrano et al., 2011a*). The PDSI is based on a primitive water balance that

71   incorporates prior precipitation evaporation demand, moisture supply, runoff, and soil water-

72   holding capacity (*Vicente-Serrano et al., 2010; Zhang et al., 2015; Wang et al., 2015*). Despite

73   its physical foundation and the inclusion of evaporative demand, it lacks multi-scalar

74   characteristics. This is a critical weakness of PDSI because drought is a multi-scale phenomenon

75   (*Vicente-Serrano et al., 2011*). In contrast, SPI has the advantage of quantifying drought on

76   different time scales and has been used by the WMO as a reference drought index (*McKee et al.,*

77   *1993; Hayes et al., 2011; WMO, 2012; Telesca et al., 2013*). However, SPI also has

78   shortcomings in that it considers only precipitation data without using evaporative demand,

79   thereby neglecting the effects of global warming (*Taylor et al., 2012; Teuling et al., 2013;*

80   *Beguería et al., 2014; Cook et al., 2014; Zhang et al., 2015; Xu et al., 2015*).

81   More recently, the standardized precipitation evapotranspiration index (SPEI), developed by

82   *Vicente-Serrano et al. (2010a, b)*, takes into account the monthly climatic water balance (the

83   difference between precipitation and reference evapotranspiration, P-PET) rather than using only

84   precipitation. It combines the multi-scalar character of the SPI and the sensitivity of PDSI with

85   changes in evaporative demand (*Wang et al., 2015*). *Vicente-Serrano et al. (2015)* provided the

86   contribution of precipitation and evaporative demand to drought indices for different climates,

87   and SPEI reflects the most evident sensitivity to PET, which is mainly controlled by aridity.

88   *Vicente-Serrano et al. (2015)* also used the SPEI to reveal the increased drought severity caused

89   by temperature rise in southern Europe. Hence, SPEI has proven to be an effective tool for

90   monitoring and studying recent droughts under warming. Recently, it has been used in diverse

91   studies that have analyzed drought variability, drought atmospheric mechanisms, and drought

92   impacts over many parts of the world, including Asia, North America, Africa, Europe, and

93   Australia (Allen et al., 2011; Potop 2011; Abiodun et al., 2013; Wang et al., 2015; Zhang et al.,

94   2016).

95   In arid regions, droughts result in significant water shortages that have critical repercussions

96   on socioeconomic development (*Zhang et al., 2012; Su et al., 2015*). The dynamics of droughts

97 may become more sensitive under climate change (*Jenkins and Warren, 2015*), and the risk of

98 drought has increased as a result of the global warming that has occurred over the past half-

99 century (*Zhang et al., 2016*). Arid regions in northwestern China now face severe drought risk

100 and water crises. Obtaining a better understanding of drought variation in the past is critical to

101 managing drought risk and water crises in the future (*Zhang et al., 2012; Xu et al., 2015a*). This

102 study aims to: (1) determine the spatio-temporal variations of drought in Xinjiang, northwestern

103 China ; (2) provide evidence of increasing drought severity caused by temperature rise; and (3)

104 evaluate the response of NDVI and hydrology to drought.

105 **MATERIALS AND METHODS**

106 The study region corresponds to Xinjiang, the largest province in China, which is located in the

107 Eurasian hinterland. The province roughly spans the area between 73.66°E–96.38°E and

108 34.42°N–49.17°N and covers an area of 1.66×10^6 km^2. The province is primarily characterized

109 by desert and grasslands, and contains three mountain ranges, the Tianshan, Altai, and Kunlun

110 Mountains, that are surrounded by vast desert basins (*Fig. 1*) (*Zhang et al., 2012; Wang et al.,*

111 *2014; Chen et al., 2014*). Xinjiang is divided by the Tianshan Mountains into northern and

112 southern Xinjiang, resulting in mountain-basin systems with different hydrological conditions

113 (*Xu et al., 2004*). Xinjiang is far from any maritime influences and receives only about 158 mm

114 of precipitation a year, making it one of the driest areas in the world (*Bai et al., 2014*). The

115 precipitation distribution exhibits a clear summer pattern, reaching its maximum between May

116 and August.

117   Continuously observed monthly temperature and precipitation readings from 76 stations in

118 Xinjiang were provided by the China Meteorological Administration (CMA) for the period

119 1961–2015. To guarantee consistency, the monthly data were checked to ensure that they met the

120   expected standards. The standard requires strict quality control processes including extreme

121   inspection, time consistency check, and others before releasing these data. Pan evaporation data

122   for northwestern China for 1961–2010 were obtained from *Li et al.* (*2013*). Soil moisture data for

123   the period 1980-2010 were provided by the National Meteorological Information Center (NMIC),

124   and the depths of the five soil layers range from 0 to 10, 10 to 20, 20 to 30, 30 to 40, and 40 to 50

125   cm.

126   Streamflow and lake level data were obtained from the Dashankou station and from Bosten

127   Lake, which are connected by the Kaidu River. This river descends from the southern slopes of

128   the Tianshan Mountains (*Chen and Chen, 2014*) and runs through large irrigated areas into Lake

129   Bosten. The Dashankou station is located at the foot of the Tianshan mountains.Data from both

130   stations Observed streamflow and level data were provided by the Xinjiang Hydrology Bureau.

131   The runoff coefficient, which is defined as the ratio between precipitation and streamflow over a

132   given time period (*Chow et al., 1988*), and the monthly runoff coefficient was calculated for the

133   period 1961-2012.

134   Remote sensing is a very effective method for estimating important information about

135   spatio-temporal changes in vegetation conditions (*Gomez et al., 2008; Coops et al., 2009*). The

136   Normalized Difference Vegetation Index (NDVI) (*Rouse, 1974*) is widely used as a proxy

137   indicator of vegetation change and can be derived from the Advanced Very High Resolution

138   Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration

139   (NOAA) Polar Operational Environmental Satellite (POES) series, among others (*Gomez et al.,*

140   *2008; Eastman et al., 2013*). The newest version of the Global Inventory Modelling and

141   Mapping Studies-NDVI third-generation (GIMMS-NDVI3g) datasets has been recently released

142   with a spatial resolution of 8 km and a 15-day temporal frequency (*Zhu et al., 2013*). The

143   GIMMS-NDVI3g data for Xinjiang were extracted for the period 1982 to 2013 and used in this

144   study.

145   SPI and SPEI were used to quantify drought, as their multi-scalar character helps to determine

146   drought variability. SPEI is calculated based on the climatic balance between monthly

147   precipitation and atmospheric evaporative demand (monthly potential evapotranspiration, ET),

148   whereas SPI includes only input monthly precipitation data. We employed the Thornthwaite

149   (1948) model approach to calculate the ET. Thornthwaite (1948) correlated monthly mean

150   temperature with PET, as determined from the water balance. Willmott et al. (1985) modified

151   Thornthwaite's original approach slightly by introducing parameterization for a limited range of

152   average air temperature T (Units: ℃):

153    $$\text{PET} = \begin{cases} 0 & T < 0 \\ 16\left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right)\left(\frac{10T}{I}\right)^m & 0 \leq T < 26.5 \\ -415.85 + 32.24T - 0.43T^2 & T > 26.5 \end{cases} \quad (1)$$

154   where N is maximum number of sun hours, NDM is number of days in the month, and I is

155   heat index, which is calculated as the sum of 12 monthly index values:

156    $$I = \sum_{i=1}^{12} \left(\frac{T}{5}\right)^{1.514} \quad T > 0; \quad (2)$$

157   and m is a coefficient that depends on I:

158    $$m = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.492. \quad (3)$$

159   The SPEI is quantified through the following steps: (a) calculating the PET; (b) determining

160   the deficit or surplus accumulation of a climate-water balance (P-PET) at different time scales;

161   and (c) normalizing the water balance into probability distribution to obtain the SPEI series. In

162   our study, Gamma distribution was chosen to calculate SPI for different time scales, and the

163   SPEI index was calculated using the three-parameter log-logistic probability distribution.

164   SPI and SPEI were calculated for each month of the year, and time scales of 1, 3, 6, and 12

165   months were selected for analysis. The SPI and SPEI drought categories are listed in Table 1.

166   Drought duration was calculated at each station for each year, and a threshold value of -1 was

167   used to determine a drought condition. The duration of a drought was interpreted as the number

168   of dry months. Regional drought durations were estimated for each year.

169   The nonparametric Mann-Kendall method (M-K) recommended by the WMO (*Mann, 1945,*

170   *Kendall, 1975; Sneyers, 1990*) was used to investigate the temporal evolution of climate and

171   drought indices from 1961 to 2015. This method has been used to investigate the significance of

172   trends in various hydro-meteorological factors, including precipitation, runoff, evaporation and

173   drought indices (*Zhang et al., 2012; Tao et al., 2014; Benitez and Domecq, 2014; Potop et al.,*

174   *2014; Vicente-Serrano et al., 2014; Wang et al., 2015; Li et al., 2015*). The Pearson correlation

175   coefficient was used to investigate the relationship between drought indices and climate series.

176   **RESULTS**

177   **Temporal variations in temperature and precipitation**

178   From 1961 to 2015, annual mean temperature in Xinjiang, China, experienced a significant

179   increasing trend, with a rate of increase of 0.31°C/10a. This is considerably higher than the rates

180   of increase observed for China as a whole, or globally (0.25°C/10a and 0.12°C/10a, respectively)

181   (*IPCC, 2013*). The warming trend started to intensify during the late 1980s, then increased

182   sharply in 1997 (Figure 2a). During the recent 17-year period (1997–2015), temperature has been

183   in a highly volatile state, making this the warmest period in the last half-century. However,

184   although temperatures remained elevated during this period, there was no clear increase. As a

185   result, the period from 1997-2015 is now referred to as a "hiatus" (*Easterbrook, 2008; Easterling*

186   *and Wehner, 2009; Kaufmann et al., 2011*). Spatially, the main areas of accelerated warming

187   appear to be in northern Xinjiang. Over the past half-century, precipitation has exhibited a slight

188   increasing trend and greater decadal fluctuations. Annual precipitation remained relatively stable

189   from the 1960s to the mid-1980s, then began to increase sharply in 1987 (Figure 2b). The most

190   humid decade was the 2000s, but without the continuously increasing trend of the 1990s.

191   Spatially, the area with the most significant increase in precipitation was mainly in northern

192   Xinjiang. Some researchers have suggested that these data show a warmer and wetter trend for

193   Xinjiang *(Shi et al., 2003; Fang et al., 2013; Chen et al., 2015).*

194   **Relationship between the SPI and SPEI drought indices**

195   Monthly SPI and SPEI were estimated at four time scales (1, 3, 6, and 12 months) for all

196   selected stations from 1961 to 2015. The average SPI and SPEI were then calculated to

197   characterize drought episodes in Xinjiang (Figure 3). According to historical records, the

198   evolution of SPI and SPEI is highly consistent between stations and time scales (Cao et al.,

199   2015). Figure 4 displays the difference between the two drought indices at four lags. It illustrates

200   that SPEI became gradually lower than the corresponding SPI and that the difference has

201   increased in recent decades. Moreover, these differences were more evident over 6- and 12-

202   month lags than over 1- and 3-month lags. In late 1996, the difference became as large as −1.5.

203   On a 6-month time scale, SPI and SPEI showed large differences before the 1990s (Figure

204   4c). More wet events and fewer dry events were identified based on SPEI. Nevertheless, based

205   on SPEI, most of the 1990s and the first decades and a half of the 21st century qualify as some of

206   the most drought-intense years on record. On a 12-month time scale, both indices identified the

207   major drought periods from 1961 to 1966 and from 1976 to 1986. However, only the SPEI was

208   able to identify drought events between 1996 and 2015 (Figure 4d). In general, SPEI confirmed

209   that the most frequent droughts occurred in the 1960s, 1970s, late 1990s, and late 2000s, whereas

210   SPI identified drought conditions during the 1960s, 1970s, and early 1980s, as well as humid

211   periods.

212   The increase in temperature enhanced ET, causing excessive water consumption and thus

213   lowering the value of SPEI. In arid regions, water consumption occurs mainly through actual

214   evapotranspiration (AE/mm), as there is ample energy (radiation) available for evaporation. For

215   the 21st century, the number of drought episodes identified by SPEI was greater than the number

216   identified by SPI due to the enhanced evaporation amount.

217   Figure 5 shows the Pearson's *r* coefficients between SPI and SPEI estimated at 1-, 3-, 6-,

218   and 12-month lags in the series for all of Xinjiang, northern Xinjiang, and southern Xinjiang

219   from 1961 to 2015. Most observations showed a high correlation between SPI and SPEI. The

220   correlations among the drought indices was notably stronger over shorter time scales than over

221   longer time scales, varying between 0.67 for a 1-month lag and 0.44 for a 12-month lag for the

222   whole region. Spatially, the correlation between 12-month SPI and SPEI was very high in

223   Xinjiang, with 86% of observations reaching the 99% significance level. Correlations between

224   SPEI and SPI were notably stronger in northern Xinjiang than in southern Xinjiang at all four

225   time scales (Fig. 5).

226   **Evidence of increasing drought caused by temperature rise**

227   The 12-month SPI and SPEI series showed coherent variation in Xinjiang before 1997 (Fig.

228   6). A major drought in Xinjiang was observed from 1975 to 1986, after which both indices

229   identified smaller drought events between 1987 and 1996, with a trend towards more positive

230   values. Nevertheless, SPEI also identified increased drought severity relative to SPI between

231   1997 and 2015 (Figs. 6a and 6c). The increased drought severity is due mainly to the temperature

232   rise in Xinjiang, which is better captured by SPEI than by SPI.

233   Figure 7 shows the spatial patterns of the 12-monthly SPI and 12-monthly SPEI trends for

234   the 1961-1996 and 1997-2015 at each station. From 1961 to 1996, SPI evolved in a positive

235   direction (meaning wetter conditions) over Xinjiang; increased drought was recorded at only a

236   few stations (Fig. 7a). For 12-monthly SPEI, about 72.5% of stations showed increasing trends

237   (Fig. 7c). SPI showed increasing drought conditions from 1997 to 2015, during which time about

238   47.1% of stations in northwestern and southwestern Xinjiang had larger trend magnitudes (Fig.

239   7b). SPEI indicated a more obvious decrease than SPI at 70.5% of stations (Fig. 7d).

240   Furthermore, northwestern Xinjiang and Kunlun Mountain display obvious wetting trends during

241   this period. Hence, both indices indicated increasing drought severity in Xinjian over the last two

242   decades, but SPEI identified a larger drought region than SPI, which neglects the effect of ET.

243   The main driving force underlying evaporation changes in arid China is the aerodynamic

244   component, specifically wind speed, while the radiative component has a minor impact (*Li et al.,*

245   *2013*). Observed vapor pressure deficit (VPD) was also a primary contributor to ET changes after

246   the early 1990s (*Li et al., 2013*). The VPD exhibited an obvious increasing trend, with a rate of

247   3.9 mm/year from 1994 to 2010 (*Li et al., 2013*). This trend reduced moisture supply and

248   increased the atmospheric water-holding capacity as a result of the increase in temperature. The

249   strengthened evaporative demand was evidenced by trends in potential evaporation in Xinjiang,

250   which were observed directly by pan evaporation (Fig. 8). Annual pan evaporation data exhibit a

251   strong decreasing trend with a rate of -6.0 mm/year from 1975 to 1993. Since 1994, however,

252   this trend has reversed upward at a rate of 10.7 mm/year.

253   **Spatio-temporal extent of drought**

254   Figure 9 illustrates the average number of dry or wet months in each year from 1961 to

255   2015. Relatively long series of dry months appeared in the early 1960s, late 1970s, and early

256   1980s, and very long series of dry months occurred in the late 1990s until the 2010s. In contrast,

257   a several series of wet months occurred in the early 1970s, and a very long series of wet months

258   occurred from the late 1980s until the middle of the 1990s. The temporal variation in the number

259   of dry months showed a significantly increasing trend (0.54 mo/10a, $p<0.01$). Before 1997, there

260   were fewer than two dry months per year but the number of dry months has increased since then.

261   The average number of dry months in recent years was greater than four, and the maximum

262   number of dry months in a year was greater than seven (from 2007 to 2009).

263   Figure 10 shows the mean number of dry months per year at different SPEI time scales from

264   1961 to 2015. The results from the two indices are generally comparable before the late 1990s.

265   The number of droughts identified at 1-, 3-, and 6-month time scales was slightly less than at the

266   12-month time scale. However, a sharp transition occurred by the late 1990s. The average

267   number of dry months for SPEI-12 was four, which was greater than the numbers for shorter

268   SPEI time scales (3.5 months for SPEI at 3 and 6 months, and 2.7 months for SPEI at 1 month).

269   However, because the high frequency noise is attenuated over longer periods, it is expected that

270   the 12-month SPEI will have a higher number of dry months. Especially between 2007 and 2009,

271   the number of dry months in SPEI-12 greatly exceeds the shorter accumulation periods (7.0

272   months for SPEI-12, 5.2 months for SPEI-3 and SPEI-6, and 3.3 months for SPEI-1). Periods

273   during which temperature increases (and precipitation decreases or remains constant) will

274   probably increase this difference.

275   Next, the percentage of stations with dry months (SPEI≤-1) was considered to investigate

276   the spatial variation of drought severity. Figure 11 shows the variation in the percentage of

277   stations with more than 3 and 6 dry months at a 12-month time scale during the period 1961–

278   2010. The other cases are not listed here. A significant increasing trend in the percentage of

279   stations with more than three dry months was found in Xinjiang, with a rate of increase of

280   5.80%/decade (Figure 11). The highest number of droughts occurred after 1997, when about

281   54.93% of stations experienced drought. Widespread and severe droughts (those for which the

282   percentage of stations recording drought exceeds 60%) were recorded in 1962, 1974, 1978,

283   1997–1998, 2000–2001, 2007–2009, and 2012, with 62%, 64%, 80%, 71%, 67%, 60%, 61%,

284   75%, 89%, 89%, and 82% of stations recording drought, respectively.

285   This analysis shows that drought conditions have been aggravated over the last two decades

286   in Xinjiang. The percentage of stations with more than six dry months also showed a significant

287   increasing trend, with a rate of 4.91% /decade (p<0.05) (Figure 11). During the period 2007–

288   2008 in particular, more than 71% of stations sustained drought conditions for more than six

289   months.

290   Figure 12 shows the severe drought events mentioned above. The 1974 drought mostly

291   affected northern Xinjiang, particularly the northern slopes of the Tianshan Mountains, Urumqi,

292   the Changji region, and the Altay region (Shi 2006). The 2008 drought was one of the most

293   serious droughts in recent times with regard to drought duration, area affected, and agricultural,

294   livestock, and economic losses. The drought, which lasted from spring to autumn, was mainly

295   located in southern Xinjiang, the Tianshan Mountain region, the Yili Valley, Tacheng, Altay, and

296   the Hami region. It was reported that the drought caused the loss of 1.22 million hectares of

297   crops, 28 million hectares of grasslands, and one billion yuan in direct economic losses (Cao et

298   al., 2015; CMA 2010). The 2009 drought was persistent and affected southern Xinjiang, while a

299   slightly less severe drought occurred in the eastern and northwestern parts of Xinjiang. The

300   drought caused the Tarim River, China's longest inland river, to run dry over more than 1100

301   kilometers (CMA 2010). In the spring and summer of 2012, northern Xinjiang and the Tianshan

302   Mountains experienced severe droughts, particularly in the Yili, Tacheng, and Altay regions. The

303   droughts reduced the yield of industrial tomatoes (in one of the world's three largest industrial

304   tomato-growing areas) to less than half that of the year before

305   (http://finance.sina.com.cn/roll/20121016/110213381605.shtml).

306   Response of vegetation NDVI and hydrology to drought

307   Increased meteorological drought severity should be evident in increased impacts on

308   drought-sensitive systems, especially natural vegetation. The NDVI reflects ecosystem processes

309   and is a critical indicator for monitoring climate dryness and wetness. *Yao et al. (2017)* analyzed

310   the response of vegetation NDVI to climate change over Xinjiang from 1982 to 2013 and found

311   that the NDVI increased from 1982 to 1997, then decreased significantly after 1997.

312   The results of this study confirm a strong negative correlation (r = -0.52; p<0.01) between

313   NDVI and an increase in PET, but the correlation between NDVI and precipitation does not

314   show a clear relationship. Nevertheless, the relationship between the NDVI and SPEI (r = 0.37;

315   p<0.01) shows a stronger correlation than that between the NDVI and SPI (r = 0.22; p<0.05),

316   implying that the decrease in vegetation NDVI is mainly controlled by PET. PET influences

317   vegetation NDVI by affecting soil moisture and plant transpiration, which eventually leads to

318   soil moisture loss (*Li et al., 2015*). Soil moisture in Xinjiang has recently shown a marked

319   decreasing trend, which is especially obvious in shallow soil layers (Figure 13 and Table 2).

320   Climate warming increases soil moisture loss and cause the death of shallow-rooted plants (*Li et*

321   *al., 2015*). Consequently, NDVI decrease and soil moisture loss have almost the same effect as

322   climate dryness.

323   Drought trends and their relation to water resources are directly related to hydrological

324   drought in China (*Shen and He, 1996; Zhai et al., 2010*). Drought at the 12-month time scale is

325   relevant for hydrological impacts (*Benitez and Domecq, 2014*). Runoff in some of the larger

326   rivers in arid China has shown a widespread "sharp" increasing trend from 1961 to 2010 (*Chen*

327   *et al., 2015*), and a "sharp" increase in the early 1990s, especially in the Tarim River basin (*Chen*

328   *et al., 2015)*. In this study, long series of runoff data for typical rivers in Xinjiang were analyzed,

329   including for the Kaidu River (one of the four main source streams of the Tarim River), which

330   has not been influenced by human interference and regulation. This analysis discovered a

331   significant upward trend (11.2 mm/ decade, $p<0.01$) in measured runoff in the Kaidu River from

332   1960 to 2010 (Figure 14b), with a 26.5% increase after the early 1990s. Figure 14 (a and b)

333   displays the evolution of runoff and precipitation in the Kaidu River basins, and there have a

334   strong correlation ($r = 0.70$; $p<0.01$). Nevertheless, the runoff coefficient shows a significant

335   increase since 1990 (Figure 14c), implying that runoff has increased more than precipitation.

336   Figure 15 presents the positive relationship between PET and the runoff coefficient of 68 rivers

337   in arid China. This coincides with a marked increase in mountain temperature and drought

338   indices (Figure 14d), suggesting that increased meltwater from glaciers and snowpack may be

339   contributing to incremental runoff. Furthermore, it is noteworthy that the rate of increase in

340   precipitation has diminished since the beginning of the 21st Century (Figure 14a). Hence, the

341   decrease in drought indices is consistent with decreased P (Figure 14d). Lake Bosten, China's

342   largest inland freshwater lake, is the outlet lake of the Kaidu River. The decrease in observed

343   lake level has become more acute since the start of the 21st century, coinciding with the

344   evolution of increased drought (Figure 14e). In addition, these developments are associated with

345   large lake areas that favor direct evaporation under increased PET.

346   **DISCUSSION**

347   Climate change in Xinjiang is complex and responds sensitively to global warming *(Chen et al.,*

348   *2012; Xu et al., 2013; Chen et al., 2015)*. *Shi et al. (2002)* found a climatic transition from warm-

349   dry to warm-wet in Xinjiang in the early 21st century based on observed data. Most evidence for

350   hydroclimatic and environmental change in Xinjiang since then has strongly supported this

351   observation (*Shi et al., 2003; Shi et al., 2007; Zhao et al., 2009; Xu et al., 2010; Li et al., 2011;*

352   *Li et al., 2012; Li et al., 2013; Yao et al., 2017*). *Fang et al.* (*2013*) further confirmed this

353   climatic transition in Xinjiang based on Coupled Model Inter-comparison Project-Phase 5

354   (CMIP5) model simulation results. We provide a latest observed data of climate change under

355   global warming. The data indicate that warming started to accelerate during the late 1980s and

356   underwent a sharp increase in 1997, after which temperatures remained highly stable (the

357   warming hiatus). Meanwhile, precipitation exhibited a sharp increase in 1987, but has remained

358   in a relatively stable state since then. As mentioned earlier, temperature and precipitation have

359   exhibited a dramatic change under global warming.

360   *Li et al.* (*2016a*; *2016b*) demonstrated that drought relief resulted from the local climate

361   becoming warmer and wetter in Xinjiang, as indicated by the precipitation-based drought

362   indices. *Zhang et al.* (*2012*) also confirmed that SPI-based evaluations of drought severity in

363   Xinjiang have lessened in recent years. In contrast, the results of this study indicate that SPEI-

364   based drought severity has been aggravated in the last two decades as a result of temperature

365   rise. The Xinjiang region has been experiencing increased drought severity since 1997 as a

366   consequence of a significant increase in temperature (1.1°C for two decades) coupled with an

367   insignificant increase in precipitation (3.5 mm/10a). Drought conditions have been exacerbated

368   by higher evaporative demand, which increased by 10.7 mm annually from 1994 to 2010.

369   The major difference between the precipitation-based indices and SPEI is the

370   meteorological factors used to calculate the indices, *i.e.*, P and P-PET respectively. SPI considers

371   only climatic water supply, whereas SPEI considers both climatic water supply and demand (*Xu*

372   *et al., 2015b*). Precipitation is a critical meteorological driver of drought, but rising temperatures

373   are playing an increasingly strong role in influencing drought severity (*Xu et al., 2015b; Vicente-*

374   *Serrano et al., 2014*). SPEI is therefore a better indicator than SPI under climatic warming

375   because it is sensitive to temperature.

376   Climate change effects on droughts have been found to exhibit similar characteristics at

377   specific sites. *Vicente-Serrano et al.* (*2014*) suggested that drought severity has increased in

378   southern Europe as a consequence of temperature rise. *Sun and Ma* (*2015*) also reported

379   increasing drought severity over the Loess Plateau in China because of the combined effects of a

380   significant increase in average temperature and an insignificant decrease in precipitation. The

381   results described here are consistent with these results. This pattern of drought severity caused by

382   temperature rise is probably applicable to other arid and semiarid areas of the world.

383   **CONCLUSIONS**

384   In this research, two multi-scalar drought indices were used: the Standardized Precipitation

385   Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI). The evolution

386   of meteorological drought was investigated in Xinjiang, northwestern China, for the period 1961-

387   2015 .. This study provides evidence for increasing drought severity caused by temperature rise

388   and discusses the effects on vegetation and water resources. A summary of the main results

389   follows:

390   (1) Temperature and precipitation in Xinjiang exhibited a dramatic change between 1961

391   and 2015. Temperature experienced a sharp increase in 1997, after which it has remained highly

392   volatile and exhibited a recent warming hiatus. Precipitation showed a sharp increase in 1987,

393   but the increasing trend has diminished over the past two decades.

394   (2) The evolution of SPI and SPEI displayed a high level of agreement for most stations and

395   time scales. SPI and SPEI showed increasing trends before 1997, after which the trends reversed.

396   Between 1997 and 2015, SPI showed increasing drought conditions at 47.1% of the stations in

397 northwestern and southwestern Xinjiang, especially at stations in the southwestern Tarim River

398 Basin. SPEI showed increased drought severity across 70.5% of stations.

399   (3) SPEI-based drought severity was significantly aggravated relative to that based on SPI,

400 which is independent of the effect of evaporative demand. Potential evaporation exhibited a

401 strong increasing trend at a rate of 10.7 mm/year. Meteorological drought severity over the last

402 two decades has been exacerbated by greater evaporative demand caused by a significant

403 increase in temperature (1.1°C) coupled with an insignificant increase in precipitation (0.35 mm

404 annually). Increased meteorological drought severity has had a direct effect on NDVI and river

405 discharge.

406

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699

Drought classifications of SPI and SPEI

Table 1. Drought classifications of SPI and SPEI.

Category	Index value
Extremely wet	Value≥2
Moderately wet	1.5≤Value <1.99
Slightly wet	1≤Value <1.49
Near normal	−0.99<Value <0.99
Mild drought	−1.49<Value≤−1
Moderate drought	−1.99<Value≤−1.5
Extreme drought	Value≤−2

Temporal changes of (a) annual mean temperature (b) and annual precipitation in Xinjiang during 1961–2015.

Table 2. **Mean value and tendency of soil moisture at each depth (0-50 cm) in Xinjiang**

Depth (cm)	0~50	0~10	10~20	20~30	30~40	40~50
Mean Value (%)	11.3	9.5	10.7	11.5	12.0	12.9
Trend (%/10a)	-3.8*	-3.6*	-4.0*	-3.5*	-3.0*	-2.3*

Figure 1

Study area and meteorological stations in Xinjiang (Yao et al., 2018).

Blue box represents the Kaidu River basin.
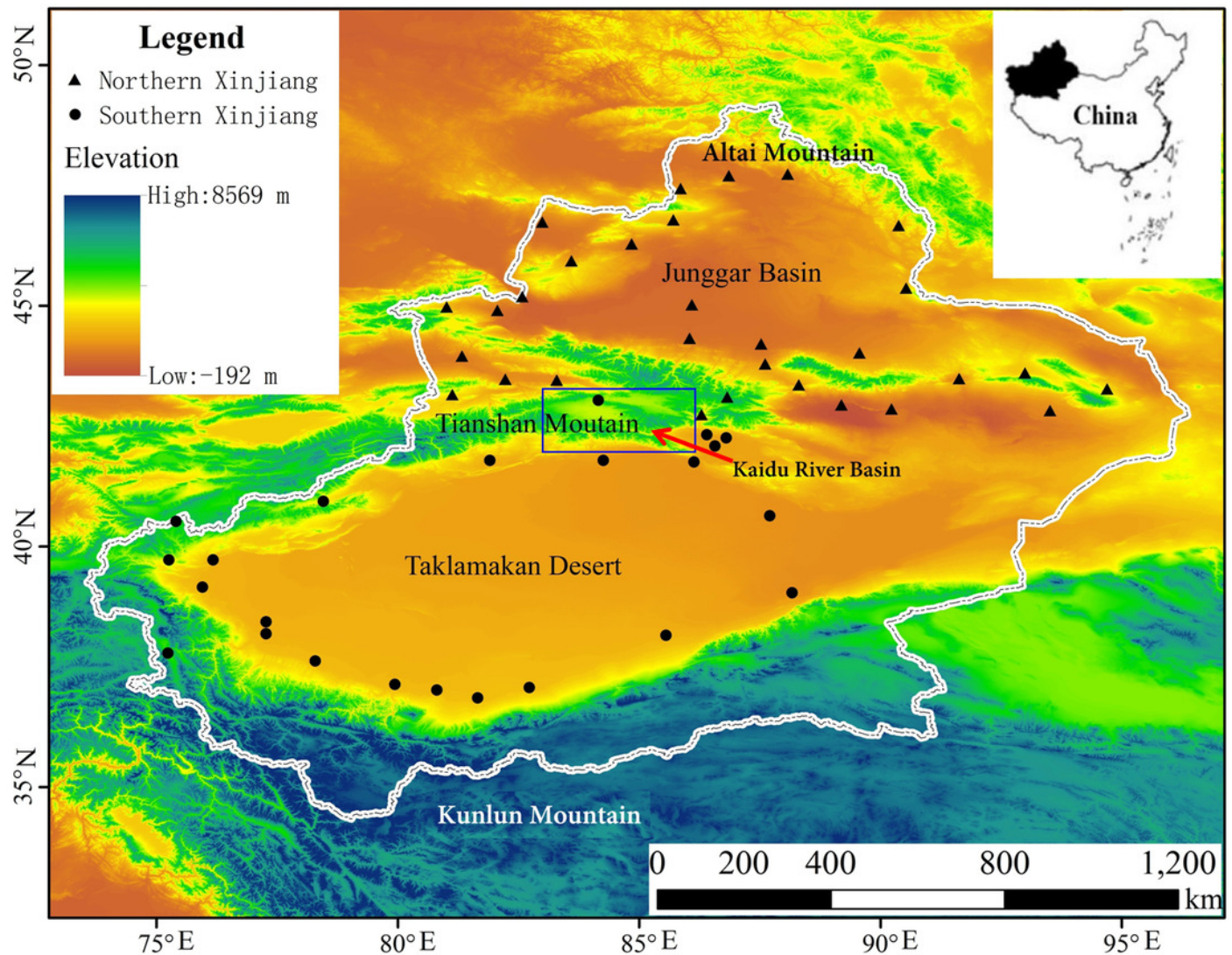
Figure 2

Temporal changes of (a) annual mean temperature (b) and annual precipitation in Xinjiang during 1961–2015.
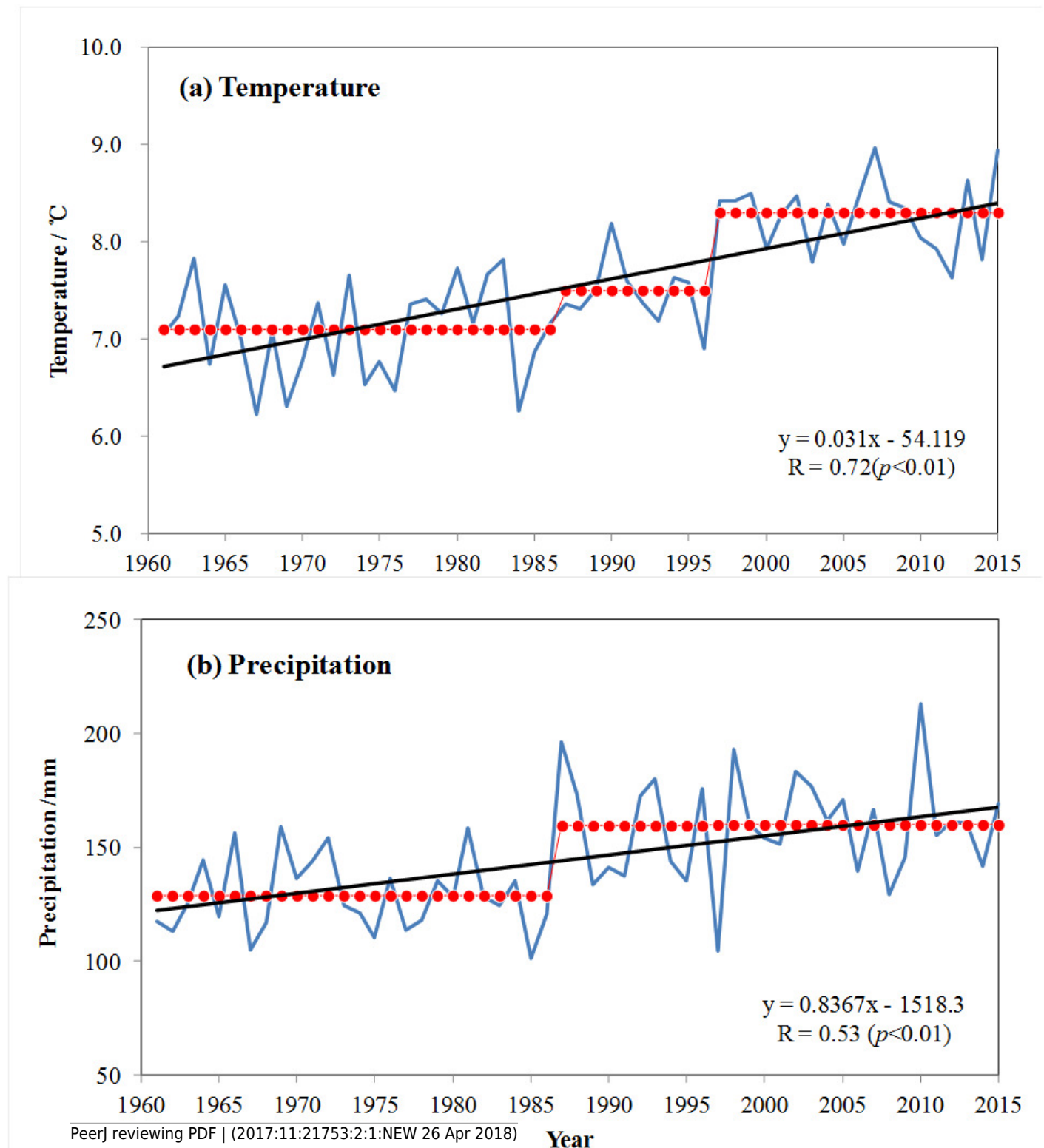
Figure 3

Evolution of the 1-, 3-, 6-, and 12- month SPEI (a-d) and SPI (e-h) for the Xinjiang, China
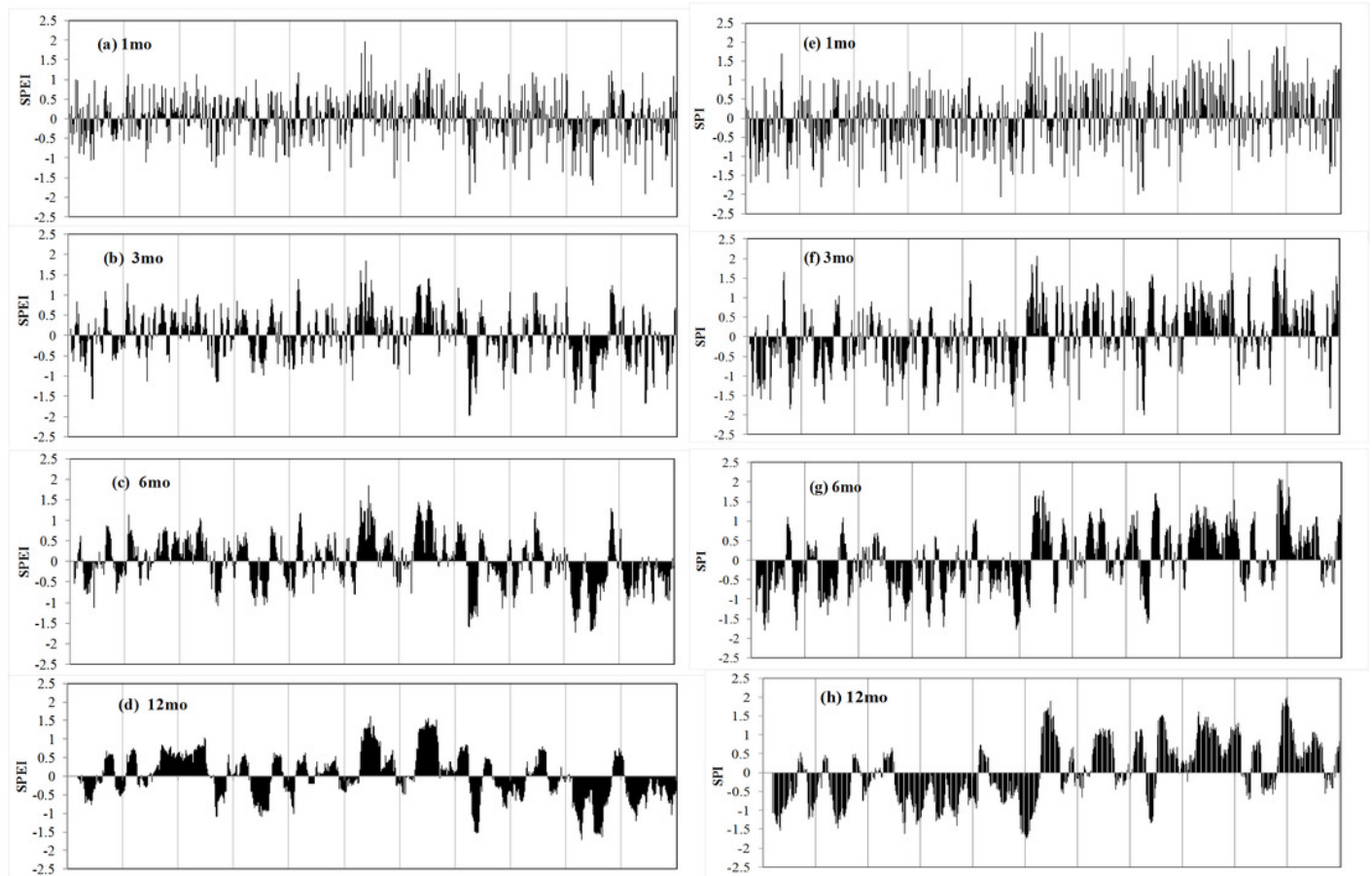
Figure 4

The difference between SPEI and SPI at 1-, 3-, 12- and 48-month lags, the ordinate denotes the value using SPEI minus SPI.

(a) SPEI-SPI 1mo

(b) SPEI-SPI 3mo

(c) SPEI-SPI 6mo

(d) SPEI-SPI 12mo

1961-1 1966-1 1971-1 1976-1 1981-1 1986-1 1991-1 1996-1 2001-1 2006-1 2011-1 2016-1

false
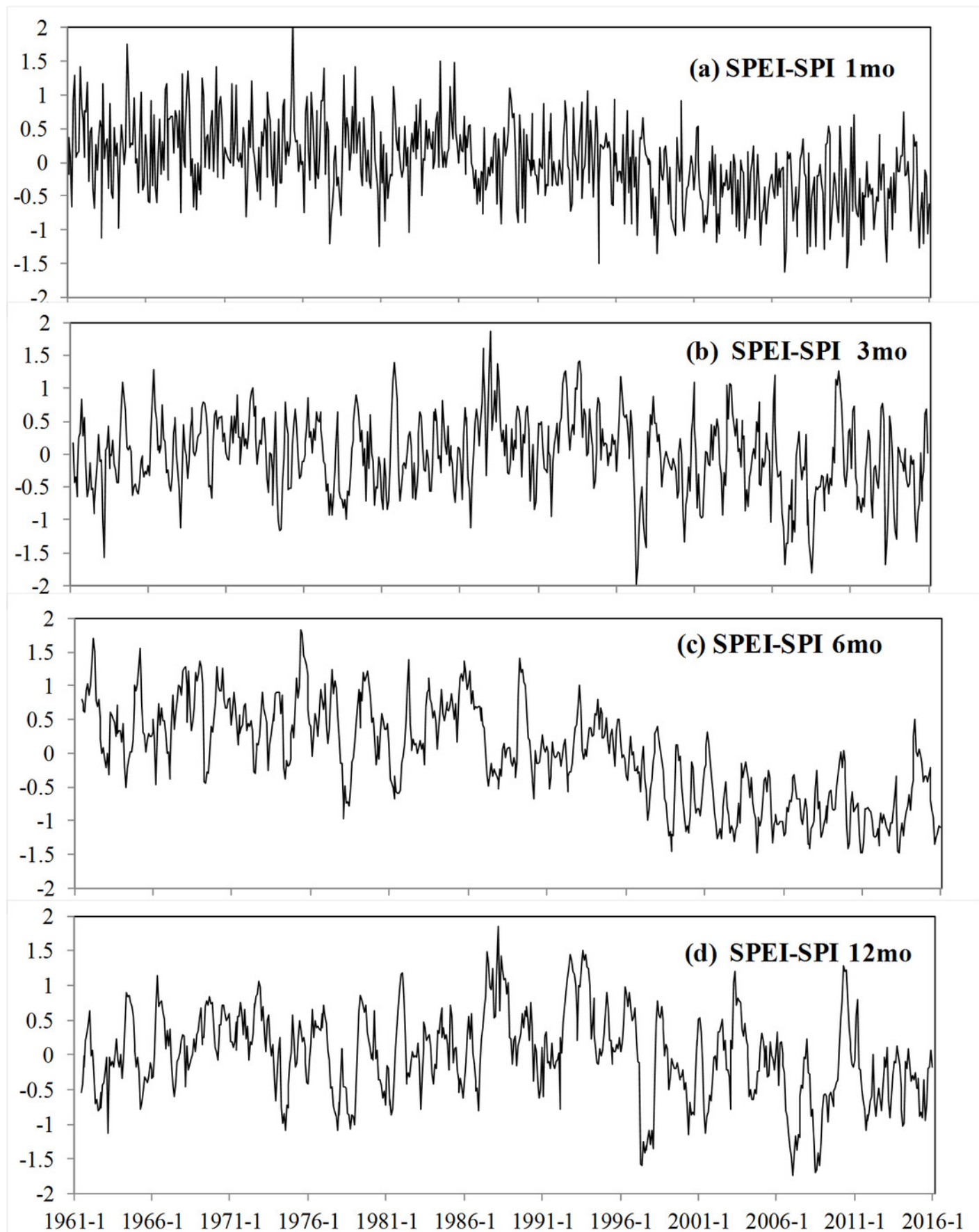
Figure 5

Pearson's r correlations between the time series of the two drought indices of the 1-, 3-, 6-, and 12- month SPI (X axis) and SPEI (Y axis) for the whole Xinjiang (a-d), Northern Xinjiang (d-h) and Southern Xinjiang(i-l) during the 1961-2015.
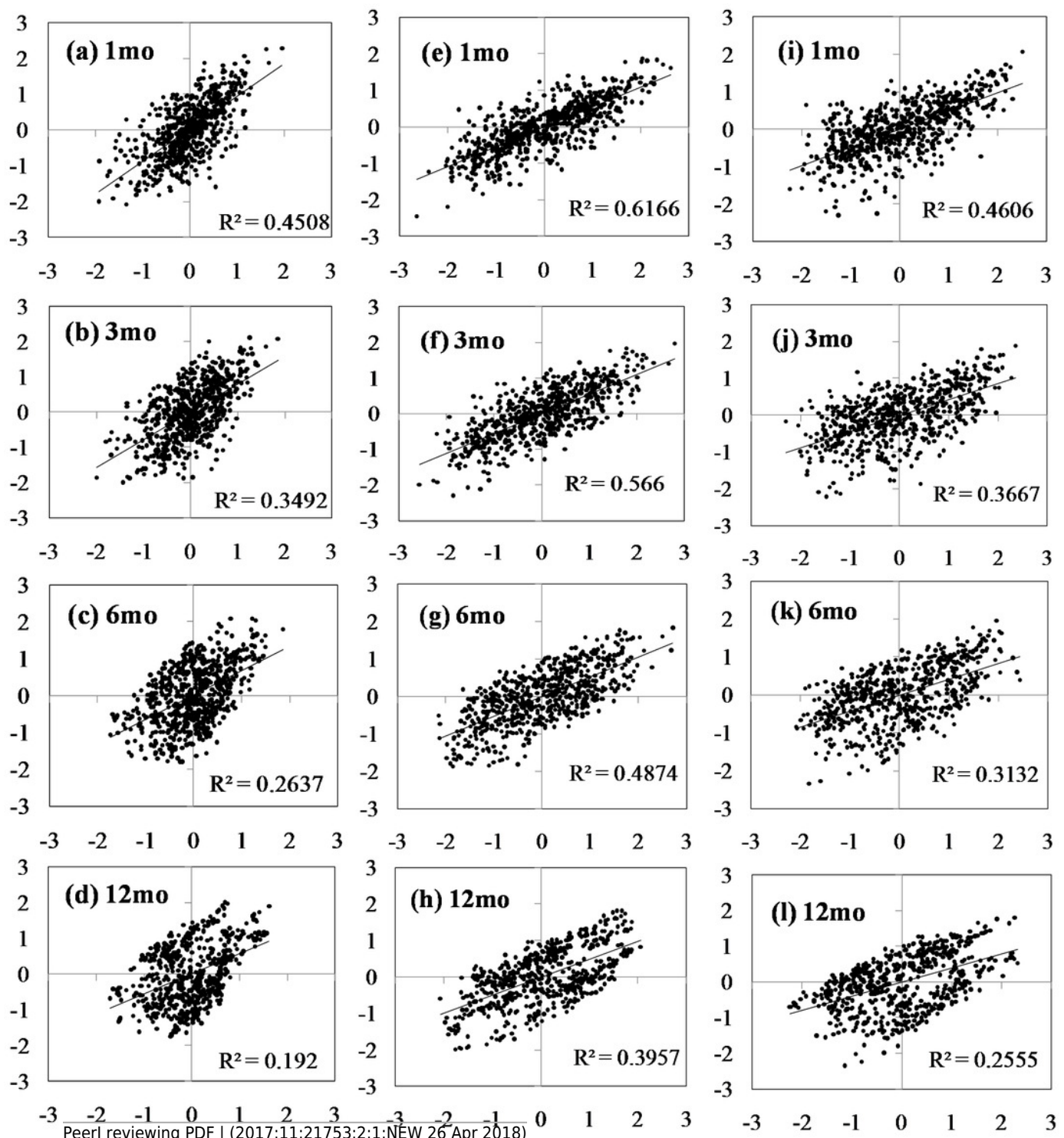
Figure 6

Evolution of the regional SPI (blue line)) and the SPEI (red line) for the Xinjiang from 1961 to 2015 (a), the scatter diagram of the SPI and SPEI at the both episodes (b. 1961-1996; c. 1997-2015)
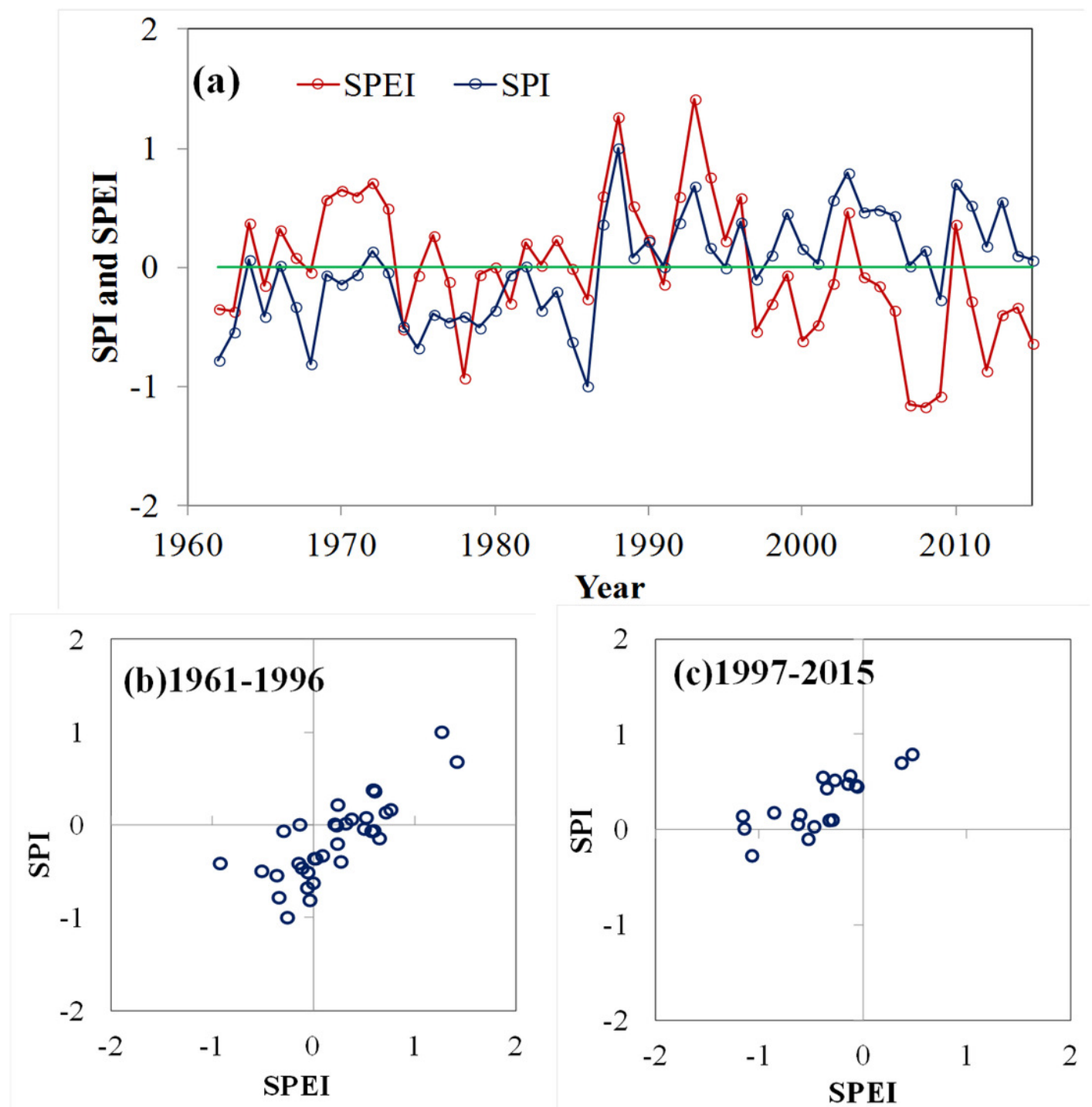
Figure 7

The spatial distribution of the temporal trends per decade in 12- monthly SPI and the 12- monthly SPEI for the period 1961–1996 and 1997–2015 in the Xinjiang.
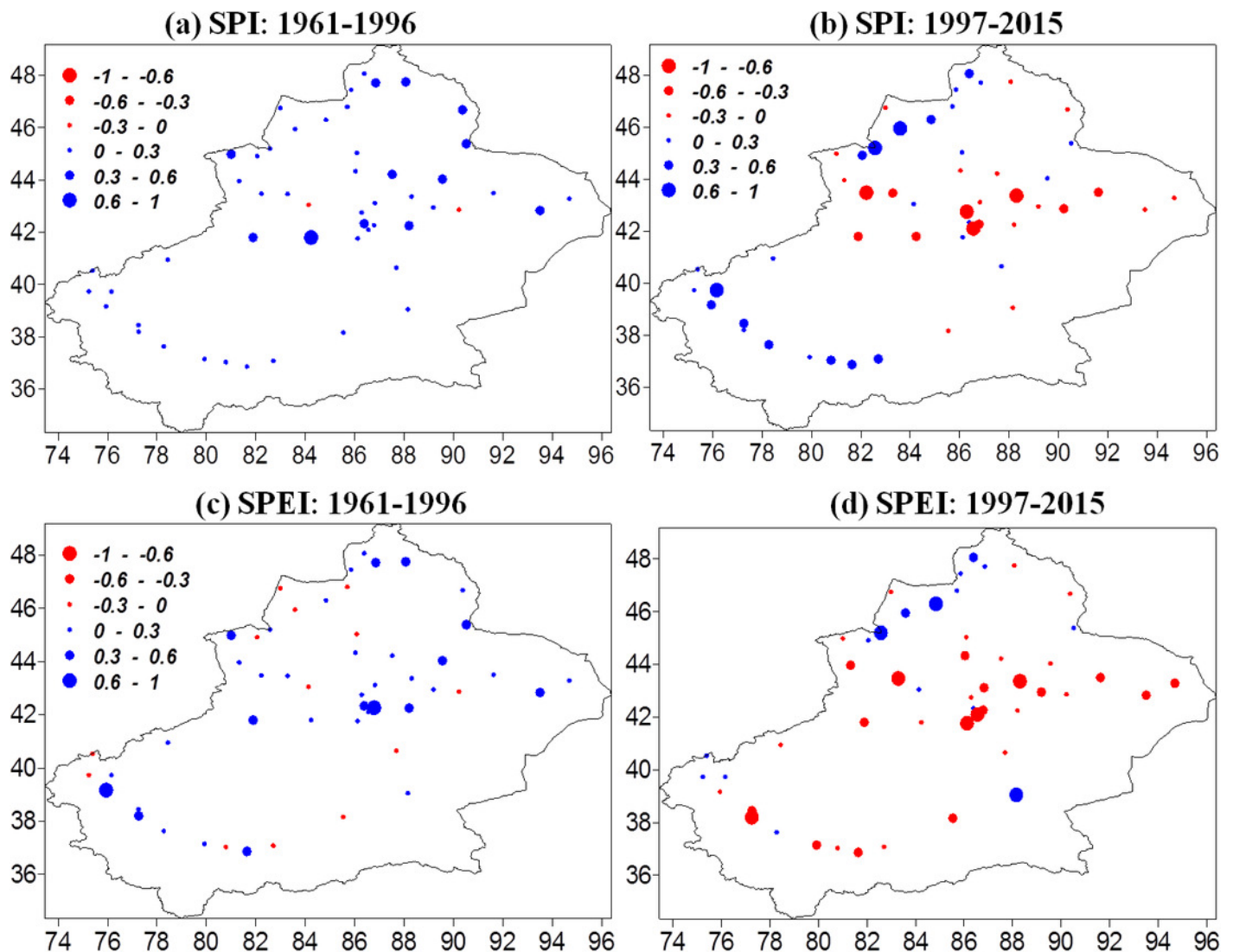
Figure 8

Evolution of the standardized Thornthwaite ET (red line) and pan evaporation (blue line) in Xinjiang. The Pearson's r correlation for the common period (1961–2010) was 0.87 (p < 0.01)
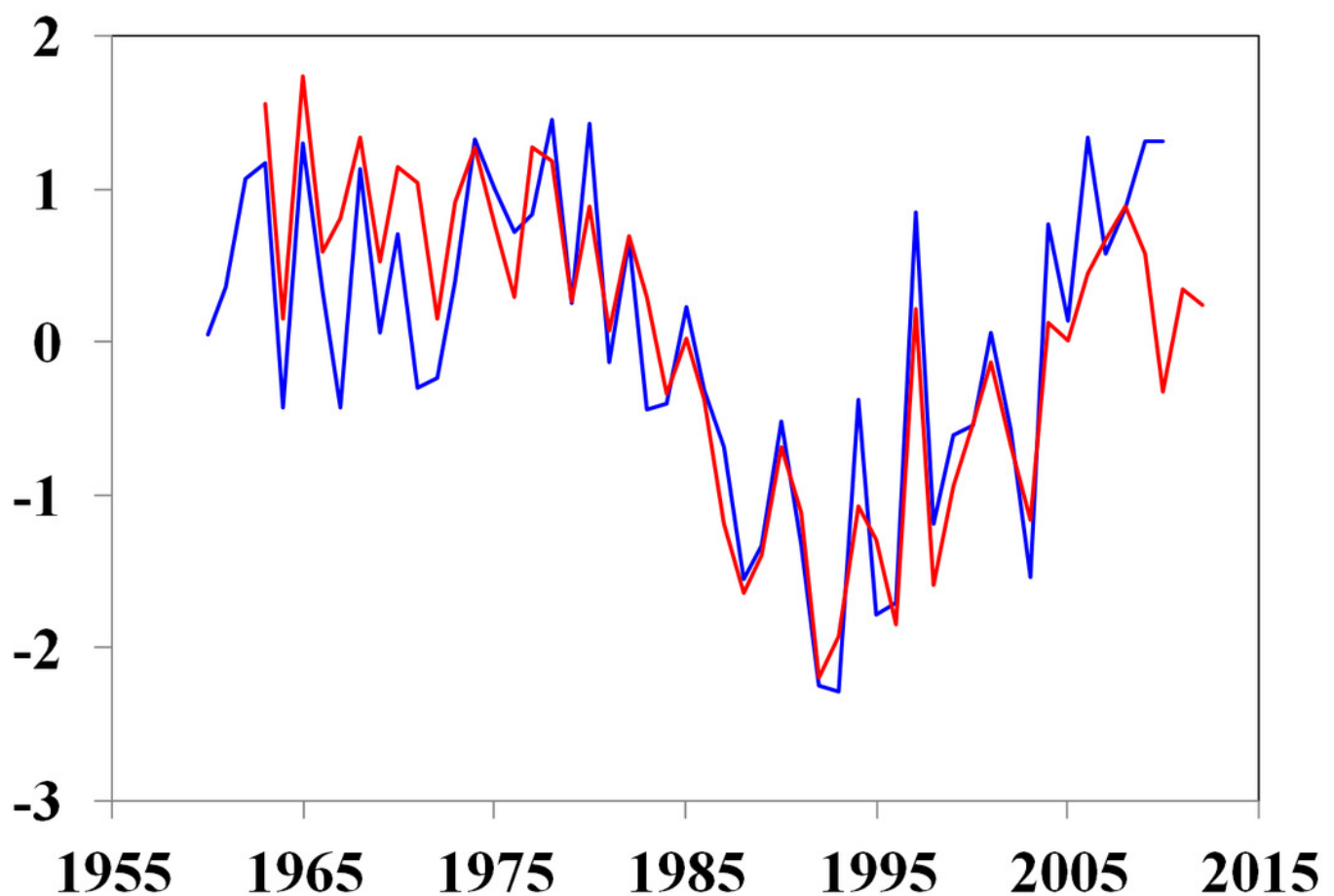
Figure 9

The mean number of dry (SPEI≤−1) and wet months (SPEI≥1) each year by the 12-month time scale from 1962 to 2015

ript to be reviewed
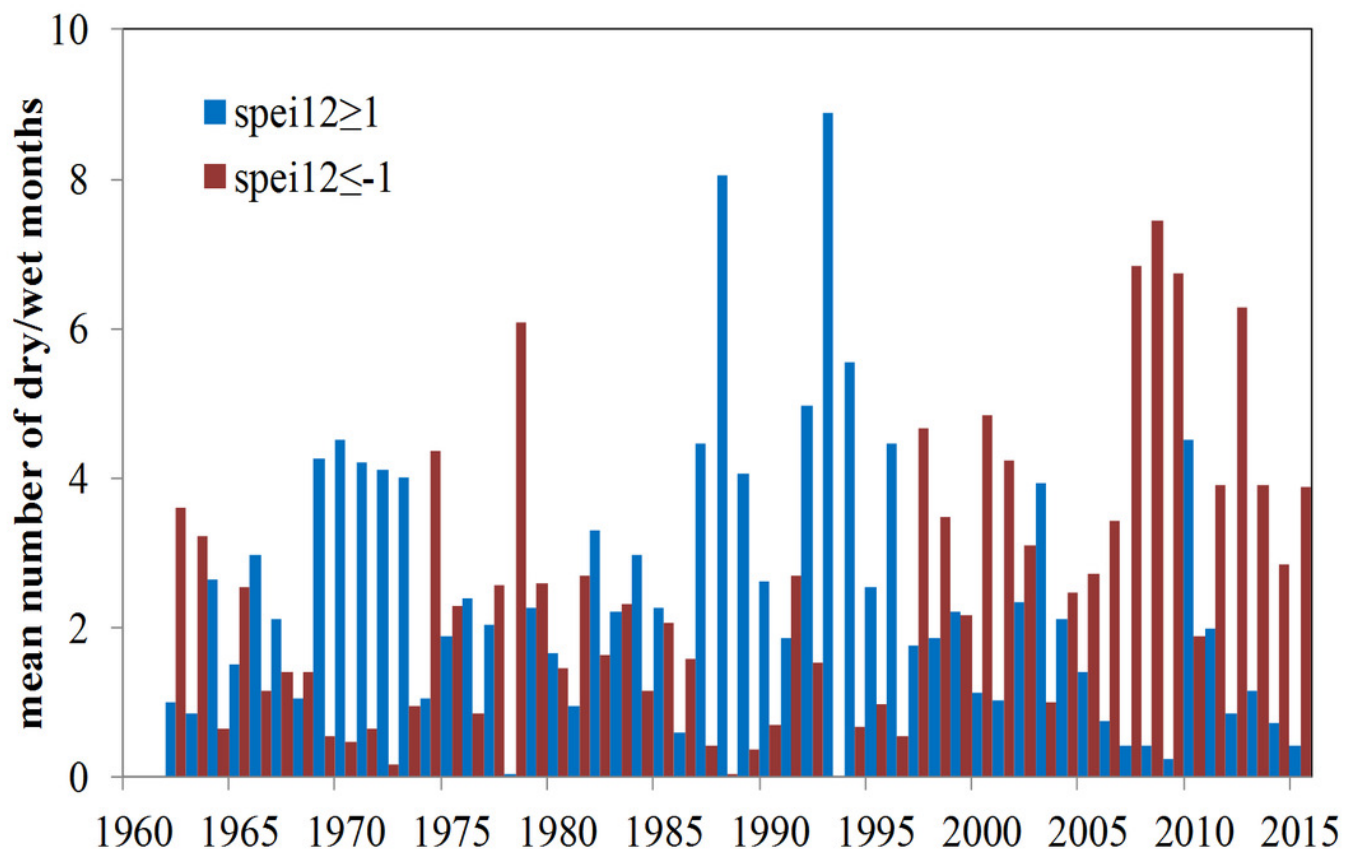
Figure 10

The mean number of dry months (SPEI≤−1) each year from 1961 to 2015
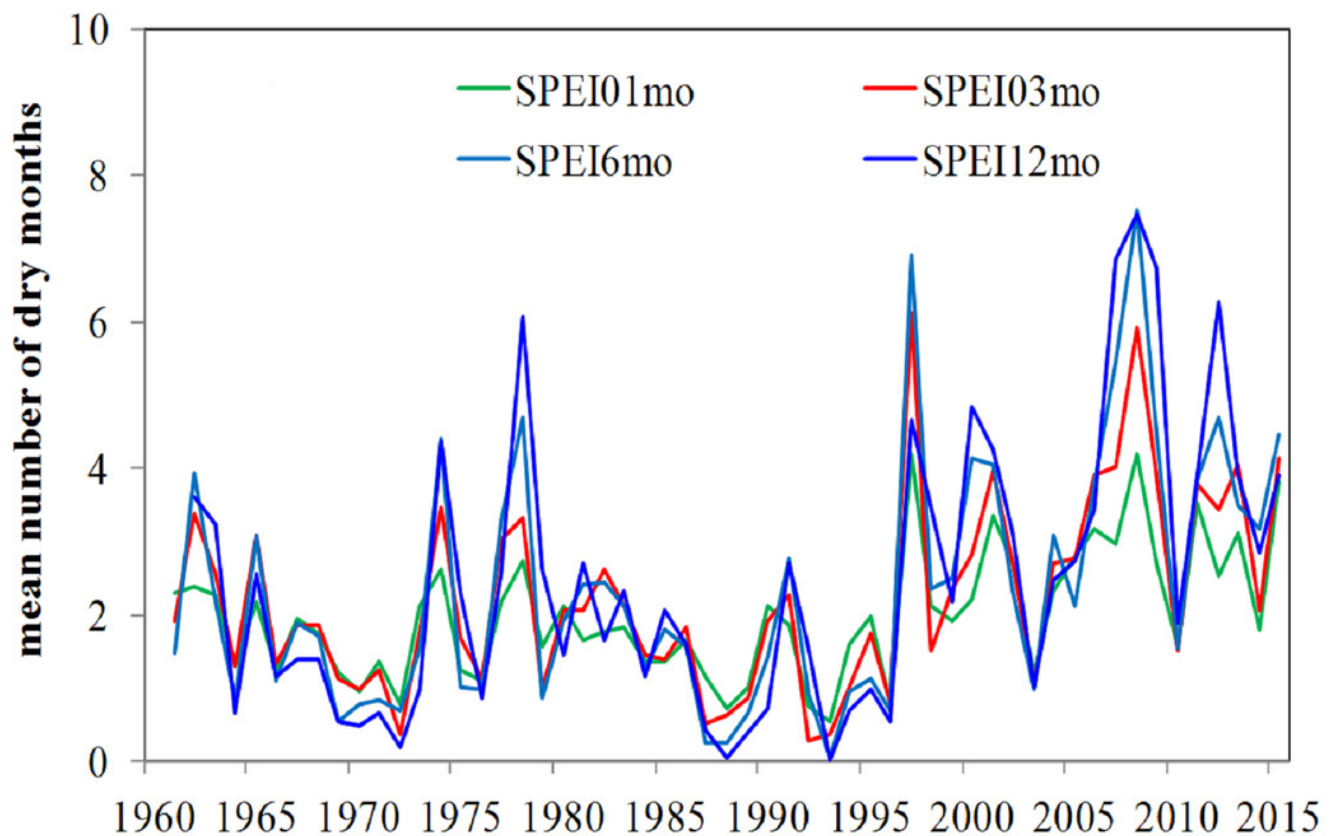
Figure 11

Percentage of stations with more than three dry months and more than six dry months each year
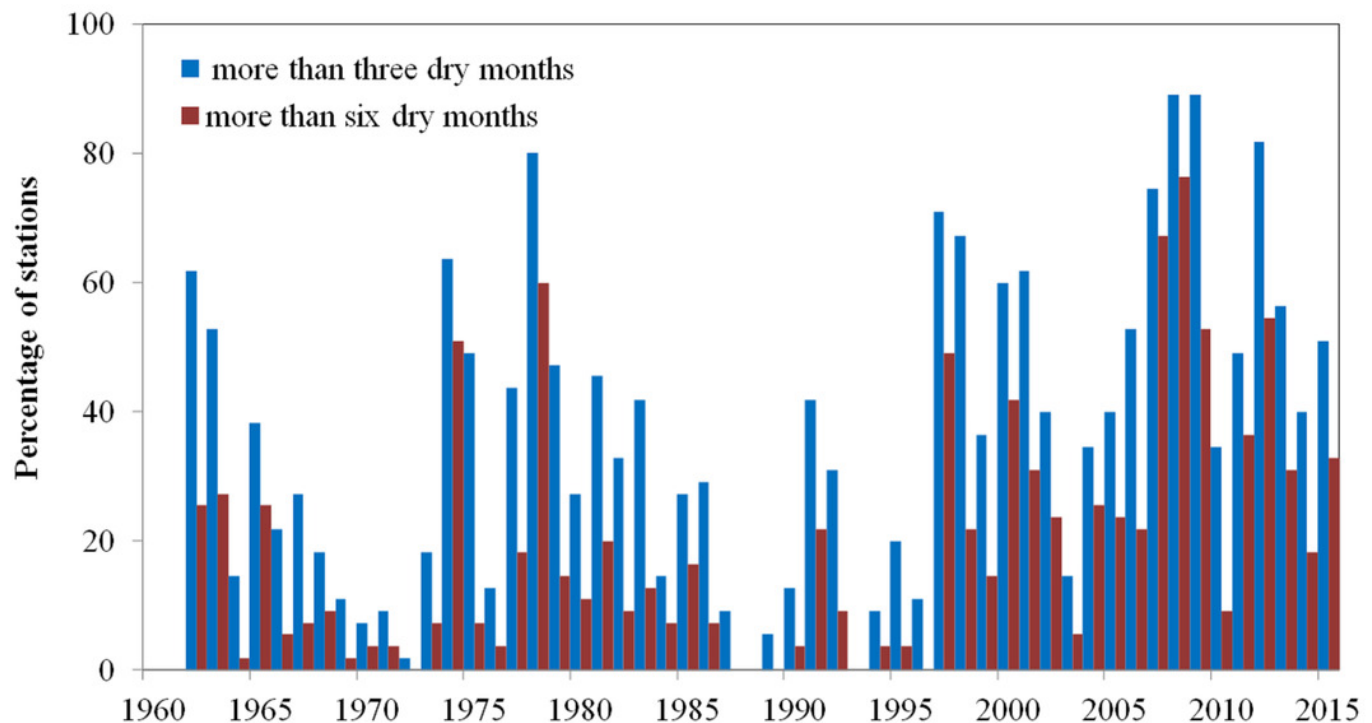
Figure 12

Spatial variations of severe drought events: (a) 1974, (b) 2008, (c) 2009, and (d) 2012
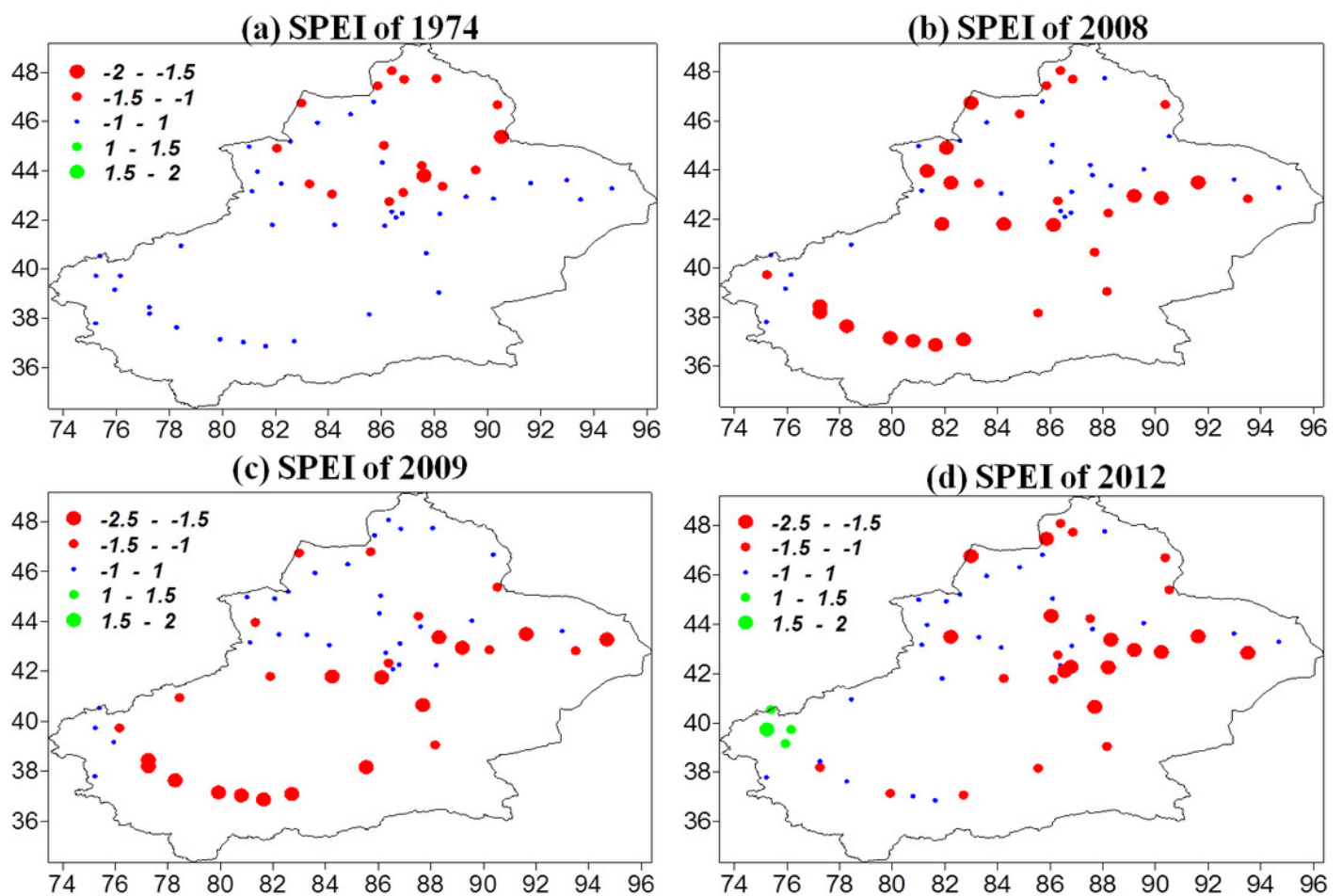
Figure 13

Annual variation of soil moisture at each depth (0-50 cm) in Xinjiang, China
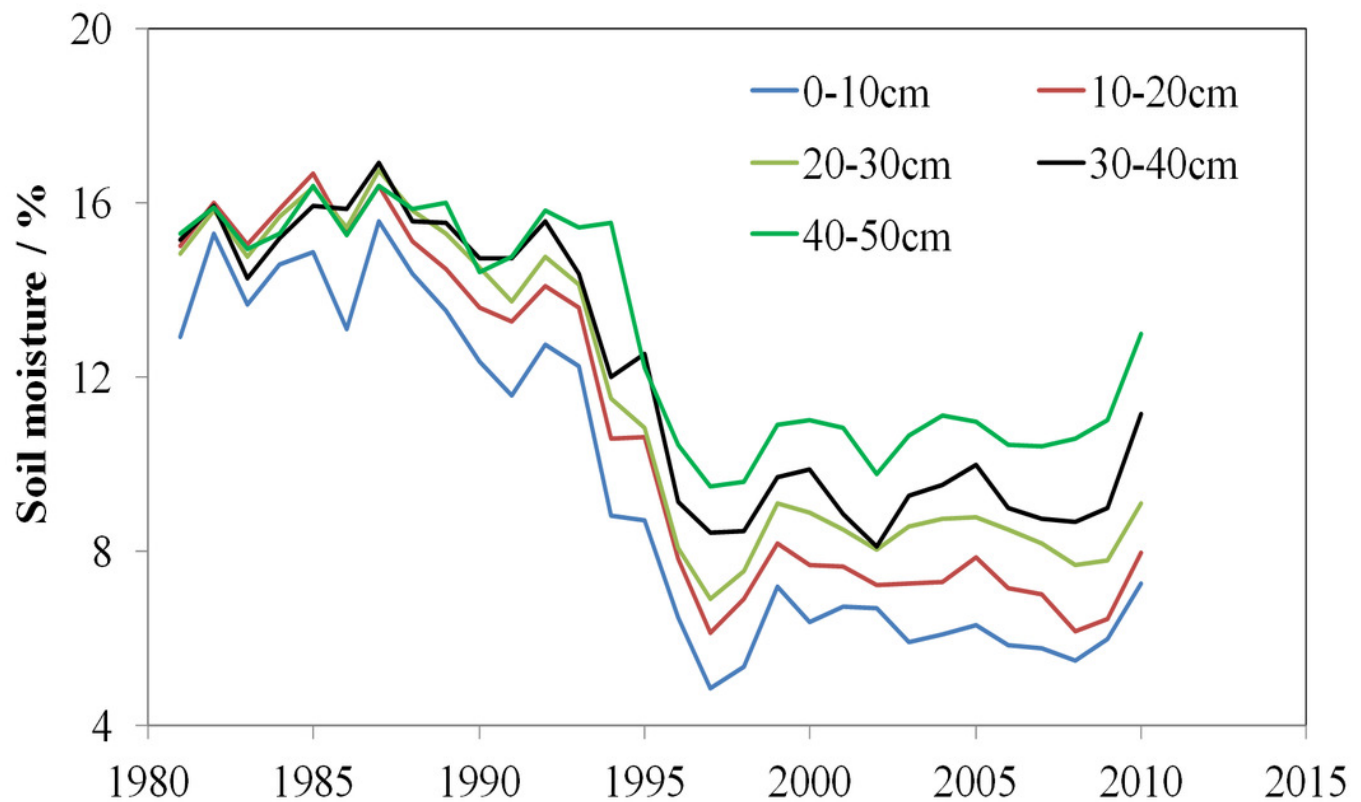
Figure 14

Evolution of parameters in the Kaidu River basins of the southern Xinjiang, China

Evolution of parameters in the Kaidu River basins of the southern Xinjiang, China, including: (a) total annual precipitation; (b) total annual streamflow at the Dashankou hydrological station; (c) runoff coefficient (ratio between precipitation and streamflow); and (d) SPI and SPEI at the Bayinbuluke climate station; and (e) water level at the Bosten Lake.

(a)

a= 0.52
r = 0.18

(b)

a = 0.04
r = 0.16

(c)

a= -0.0005
r = 0.11

(d)

SPEI   SPI

(e)
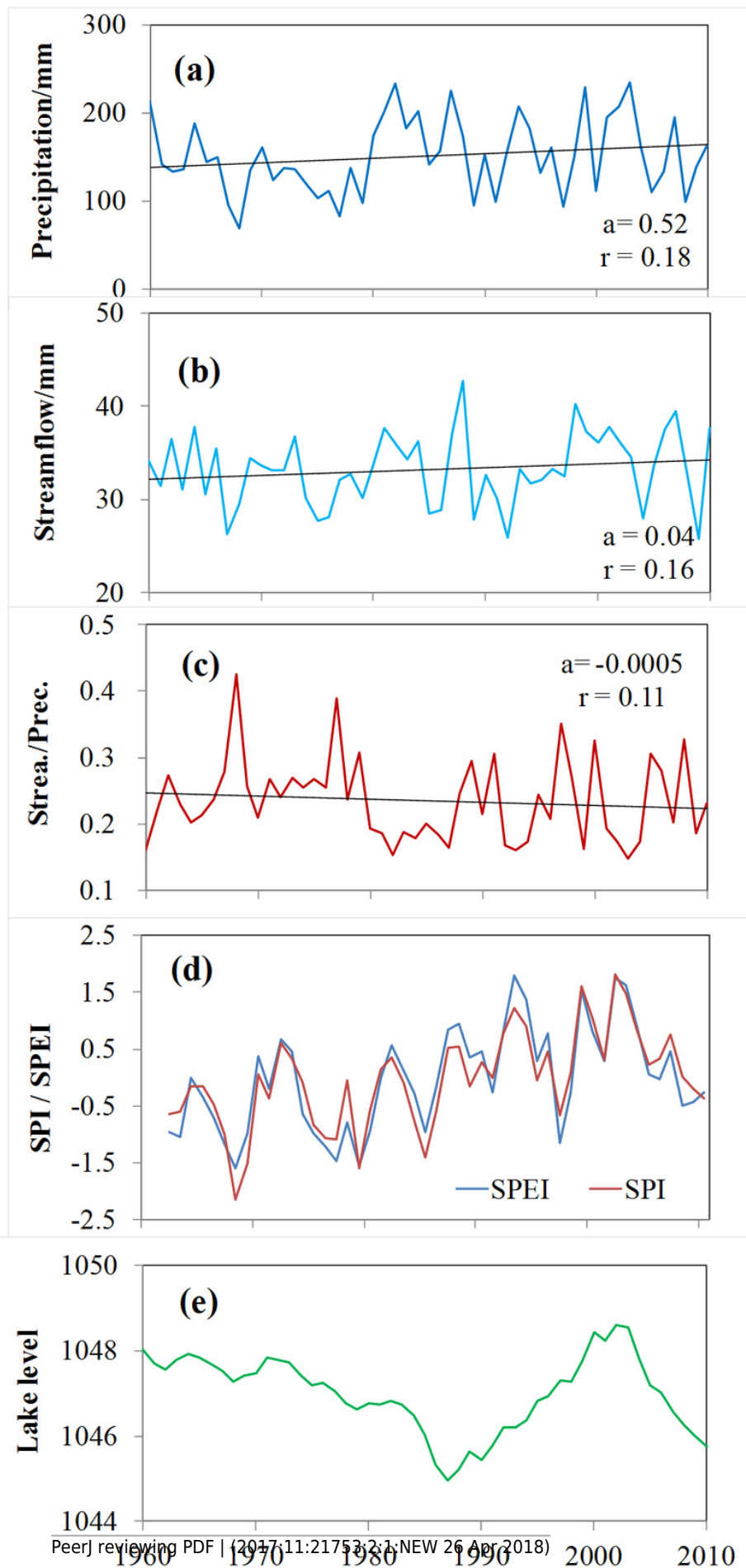
Figure 15

The scatterplot between annual ET and the annual streamflow/precipitation ratio of the 68 inland river catchments in northwestern China