

The spatial and temporal analysis of precipitation concentration and dry spell in Qinghai, northwest China

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Abstract Understanding precipitation variations from various aspects is important for the assessment of drought risk and the utilization of water resources. The precipitation concentration index (PCI) and the concentration index (CI) were used to investigate/quantify the heterogeneity of the monthly and daily rainfall in Qinghai province that is part of northwestern China, respectively. The precipitation concentration in Qinghai shows a significant irregularity of the monthly rainfall distribution and highly homogeneous distribution of the daily rainfall. It is found that PCI and CI show negative trends at most stations. Meanwhile, the spatial and temporal variation of nine dry spell (DS) indices are analyzed. From the spatial perspective, drought in the northwestern area is much severer than that in other areas of Qinghai. According to the results of temporal analysis by using the Mann–Kendall test, the number of

very long DSs, maximum length of DS, mean length of DSs, and the total dry days of extreme DS all decrease. All these results verify that the warm dry climatic pattern in Qinghai can be changed into the warm wet climatic pattern.

Keywords Qinghai · Precipitation concentration · Dry spell

1 Introduction

The general consensus is that global warming is likely to enhance the hydrological cycle, which will cause changes in rainfall amount, frequency, magnitude, intensity and duration (Degefu and Bewket 2013). Research on the changing patterns of the regional and local-scale precipitation is very important for the assessment of hydrological consequences, such as flooding and droughts in the context of climate change. Thus, a number of precipitation-related indices derived from daily and monthly data are widely used to investigate the changing patterns of precipitation. In recent studies, the precipitation concentration and dry spell (DS) have aroused much interest.

Precipitation concentration is represented not only by percentages of the annual total precipitation on several rainy days but also by the time and degree of concentration of the total precipitation within a year. In the previous works, two different indices, i.e. precipitation concentration index (PCI) and concentration index (CI), have been created to describe the magnitude of precipitation concentration from different points of view. PCI proposed by Oliver (1980) represents the degree to which annual total precipitation is distributed over 12 months. CI defined by Martin-Vide (2004) is used to evaluate the varying weight of daily precipitation and the distribution of rainy days.

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Considering their scientific and practical merits, PCI and CI are widely used to analyze the statistical structure of precipitation in many studies. For example, De Luis et al. (2010, 2011) analyzed relationship between trends of PCI and annual precipitation in Spain and found an opposite behavior between annual precipitation and seasonal PCI in Spain. Zhang et al. (2009) analysed CI at the yearly time scale and the associated spatial patterns across the Pearl River Basin, China. The recent studies by Coscarelli and Caloiero (2012), Huang et al. (2014), Shi et al. (2014) concerned changes in precipitation concentrations and the associated spatial patterns across Southern Italy, Jiangxi province, Huai River Basin, respectively, using both the two concentration indices.

DS is usually defined as a number of consecutive dry days. Drought is not only caused by insufficient total precipitation, but also directly caused and increasingly aggravated by a number of DSs. However, base on monthly precipitation amount or daily frequency only will sometimes lead to incorrect conclusions (Cindrić et al. 2010). For instance, if a prolonged dry period is followed with heavy precipitation events, this period may be concluded to be wet in an average level (She and Xia 2013). In the analyses of DSs, various statistical indicators have been used by different authors (Mathugama and Peiris 2011). Among these, the three common indicators used are the number of DS (NDS), mean length of DS (MDS) and maximum length of DS (MLDS). For example, climatological features of the mean and maximum DS durations in Croatia, as well as the frequency of long DSs (>20 days) are discussed by Cindrić et al. (2010). Six DS indices comprising of the main characteristics of DSs, the persistency of dry events, and the frequency of the short and long duration of DSs is used to identify whether or not these indices have increased or decreased over Peninsular Malaysia during the monsoon seasons (Deni et al. 2010). The recent studies by She and Xia (2013) present and analyze the spatial and temporal variability of MLDS, MDS and NDS in five time periods in Yellow River basin during the past several decades.

Qinghai province, located on the northeastern part of the Tibetan Plateau, plays a role as a major ecological barrier and water source reservoir for northwest China. The Yellow River originates in southern part of Qinghai province, while the Yangtze River and the Mekong River have their sources in the southwestern part of this province. Since Qinghai is a typical arid and semi-arid area, the drought is a frequently recurring phenomenon and is the most serious natural hazard in this province. Thus, it is very important to study the precipitation changes in this province. However, it is known that most studies about precipitation in Qinghai focused on the changes of precipitation amount (Bai et al. 2013; Yang et al. 2013). Other important aspects of

precipitation, especially the precipitation structure and consecutive no rain events have not aroused adequate attention. Therefore, the main purpose of this study is to systematically investigate long-term changes of precipitation concentration and DSs using historical observed monthly and daily precipitation from 1963 to 2012.

2 Study area and data

Qinghai province (89°E–104°E, 31°N–40°N) is an inland province including eight municipalities with a plateau continental climate. Qinghai has quite cold winters, mild summers, and a large diurnal temperature variation. Its mean annual temperature is approximately -5 to 8 °C, with January temperatures ranging from -18 to -7 °C and July temperatures ranging from 15 to 21 °C. It is also prone to heavy winds as well as sandstorms from February to April. Significant rainfall occurs mainly in summer, while precipitation is very low in winter and spring, and is generally low enough to keep much of the province semi-arid or arid. In this study, daily precipitation datasets of 39 national meteorological stations in Qinghai province were provided by the National Climate Center (NCC) of the China Meteorological Administration (CMA). On the basis of record length, 32 stations with integrated 50-year records were selected as candidate stations. The quality and homogeneity of the climatic records from these stations were checked and controlled using the RclimDex software package (<http://etccdi.pacificclimate.org/software.shtml>). After rejecting four stations with inhomogeneous daily precipitation series, 28 stations were finally selected. The locations of the 28 stations are plotted in Fig. 1.

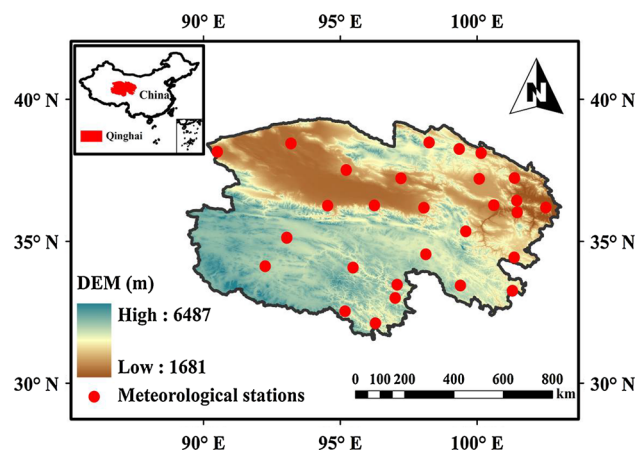


Fig. 1 Meteorological stations used in this study and location of Qinghai Province, China

3 Methodology

The spatial and temporal changing patterns of precipitation concentration and DS in Qinghai province during 1963–2012 were analyzed by the Mann–Kendall (MK) test. The detailed principles of calculating indices and methods are described in the following text.

3.1 Calculation of precipitation indices

PCI, a statistical index, was proposed as an indicator of monthly rainfall heterogeneity (Oliver 1980). It is calculated according to Eq. (1):

$$PCI = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100 \quad (1)$$

where P_i is the monthly precipitation in month i . Oliver (1980) suggests that PCI values of ≤ 10 , 11–15, 16–20 and > 20 represent the uniform precipitation distribution, moderate precipitation concentration, irregular precipitation distribution and strongly irregular precipitation distribution, respectively (De Luis et al. 2011).

CI, a statistical index, was proposed to assess the contribution of the days with different rainfall to the total amount (Martin-vide 2004). It is developed in accordance with the fact that the distribution of precipitation frequencies is generally adjustable with negative exponential distributions. Martin-vide (2004) introduces the computational procedure as follows: (1) The precipitation class limits are classified based on suitable class interval (1 mm was chosen as class interval); (2) the number of rainy days range falling into each class is counted, and the associated amount of precipitation is computed (a rainy day is defined when daily precipitation is ≥ 0.1 mm); (3) The cumulative summation of output items of Step (2) is calculated; (4) following Step (3), an exponential curve Y (accumulated percentages of precipitation) versus X (accumulated percentages of days) is derived and can be expressed as $Y = aX\exp(bX)$, where a and b are the regression coefficients estimated by the least-squares method. The area S enclosed by the bisector of the quadrant and the polygonal line provides a measure of concentration. The Gini CI $2S/10,000$ is used as a concentration measure (Martin-vide 2004). The precipitation concentration assembles the Gini coefficient, which is the area circled by the perfect distribution (45°) line and the Lorenz curve [the Lorenz curve is described by the model $Y = aX\exp(bX)$].

DS was defined as the consecutive days with the daily precipitation amount less than a certain threshold. The minimum length of a single DS is 1 day. The determination

of DS relies on the selection of threshold and analysis of DS could be done using different rainfall thresholds for a dry day, such as less than 0.1, 1.0, 5, 10 mm (She and Xia 2013). In fact, the selection of threshold is not fixed and it depends on certain characteristics, such as the climate and the needs of the each particular study area (Tolika and Maheras 2005). In this study, the threshold of classification for a dry day was chosen as 0.1 mm, which can distinguish between wet and dry days and would be associated with episodes leading to drought. This study focused on the spatial and temporal patterns of DS in Qinghai, when the annual time scale was considered. Attention was paid to the nine DSs indices (Table 1).

3.2 Mann–Kendall test

In this study, the MK trend test, highly recommended for general use by the World Meteorological Organization (Zhang et al. 2009), was used to characterize the trends for the precipitation indices and to test their significance. This test is known as the Kendall's tau statistic, which is a non-parametric test, meaning that it does not assume any priority in the distribution of the data and allows the presence of a tendency over long period of rainfall data to be observed (Yavuz and Erdoğan 2012). Hydrological time series may frequently display statistically significant serial correlation that may confound the trend analyses (Yue et al. 2002). Here, effective sample size (ESS) proposed by Yue and Wang (2004) was used to modify the variance of the MK statistic to reduce the influence of serial correlation on the MK trend. The procedure is as follows (Yue and Wang 2004): (1) remove the existing trend from the series if it exists; (2) the sample serial correlation is estimated using the detrended series; and (3) the MK test modified by ESS is applied to assess the significance of trend in the original time series. The 10 % significance level was used as a threshold to classify the significance of positive and negative MK trends.

4 Results

4.1 Spatial and temporal patterns of PCI (monthly data)

PCI proposed by Oliver (1980) represents the degree to which annual total precipitation is distributed over 12 months. Figure 2a shows the spatial distribution of PCI values, which are derived from month precipitation data sets of each individual year and averaged over the observation years. These values range from 15.5 to 35.4. It is clearly shown that the higher PCI are mostly observed in the northwest Qinghai, and the lower PCI are mainly found

Table 1 Definitions of the dry spell (DS) indices

Indices	Description	Unit
NvsDS	Annual number of the very short dry spells (the length of very short DS is between 1 and 5 days)	Events
NsDS	Annual number of the short dry spells (the length of short DS is between 5 and 10 days)	Events
NmDS	Annual number of the moderate dry spells (the length of moderate DS is between 10 and 20 days)	Events
NIDS	Annual number of the long dry spells (the length of moderate DS is between 20 and 30 days)	Events
NvIDS	Annual number of the very long dry spells (the length of very long DS is larger than 30 days)	Events
MLDS	Annual maximum length of dry spells	Days
MDS	Annual mean length of dry spells	Days
DDS95	Total dry days in the extreme dry spells (an extreme dry spell can be defined as a dry spell with duration longer than the 95th percentile of DS)	Days
CDS20	Contribution of 20 % driest spells to the total dry days	%

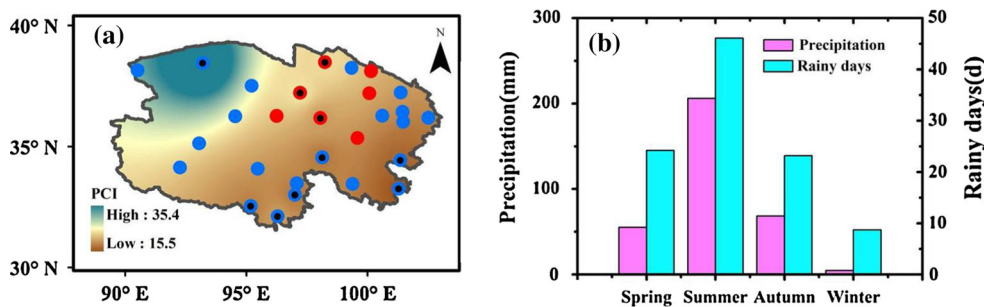


Fig. 2 a (Left panel) Long-term mean values and trends of PCI of Qinghai during 1963–2012 (Blue circles denote decreasing trends; red circles denote increasing trends; Circles with a black dot show

in some areas of east Qinghai. According to the classification of Oliver (1980), most of Qinghai is dominated by an irregular distribution of precipitation, and some areas present the strong irregularity of precipitation distribution. The seasonal distribution of precipitation and rainy days further explains the higher precipitation concentration across Qinghai (Fig. 2b). On the one hand, precipitation occurs mainly during summer, making up about 62 % of the annual total amount and 45 % of annual total rainy days. As the onset and the seasonal northward advance of the East Asian summer monsoon, different regions in East China enter their rainy seasons from south to north sequentially. At mid-July, the major rain belt reaches North China and brings rain there. Consequently, the precipitation of Qinghai mainly concentrates in summer. On the other hand, both precipitation and rainy days in winter are much lower than those of other seasons. In winter, northwest China experiences a strong winter monsoon, which brings cold-dry air from high latitudes and prevents the northward flow of warm-moist air from low latitudes (Sun and Ao 2013). Consequently, there is less water vapor available to form winter precipitation over northwest

significant trends detected by MK test at the 10 % significance level). b (Right panel) the seasonal distribution of precipitation amounts and rainy days across Qinghai

China. In general, the short rainy season and drier winter cause the higher concentration of monthly precipitation distribution.

The results of MK test for PCI series are also shown in Fig. 2a. There are 21 stations characterized by decreasing PCI, accounting for 75 % of the total number of stations. As illustrated in Fig. 2a, seven stations with significant decreasing trends are mainly observed in the south Qinghai. These results indicate that the distribution of the monthly precipitation during the year becomes more uniform in this province. The decreasing tendency of PCI across Qinghai is well confirmed by the results obtained by applying the MK test to the seasonal precipitation (Fig. 3). For both entire province and individual stations, the precipitation in spring and winter presents significant increasing trend. The obvious wet tendency found in dry season may cause the decline in PCI.

4.2 Spatial and temporal patterns of CI (daily data)

CI is used to evaluate the distribution of rainy days. The CI values range from a minimum of 0.58 to a maximum of

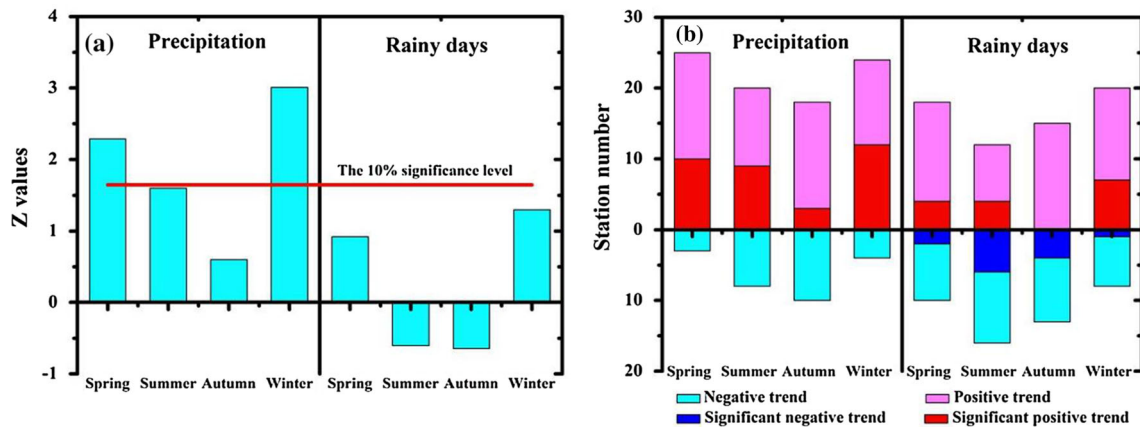


Fig. 3 **a** (Left panel) Regional trends of seasonal precipitation and rainy days in Qinghai; **b**(Right panel) number of stations with different trends for seasonal precipitation and rainy days in this province

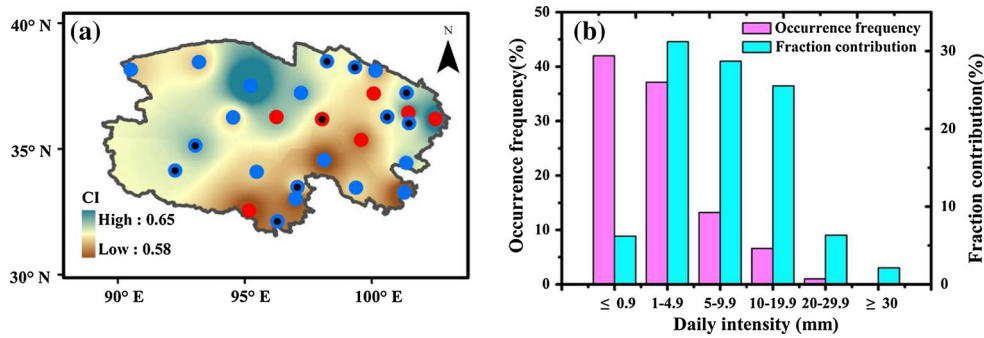


Fig. 4 **a** (Left panel) Spatial distribution of values and trends of CI of Qinghai during 1963–2012 (Blue circles denote decreasing trends; red circles denote increasing trends; circles with a black dot show significant trends detected by MK test at the 10 % significance level).

b (Right panel) occurrence frequency of daily precipitation with different intensity and fractional contribution of precipitation amount of daily precipitation with different intensity to the annual total precipitation amount across Qinghai

0.65. According to the spatial distribution of CI, the study area can be roughly divided into two parts: the northern area of this province with higher values of CI and the southern area with lower values of CI. The precipitation CI of the Pearl River Basin in south China ranges from 0.74 to 0.80 (Zhang et al. 2009), and that of Huai River Basin in central east China (Shi et al. 2014) and Xinjiang province in northwest China varies between 0.63 and 0.72, and 0.58 and 0.7, respectively. Comparatively, the precipitation CI of Qinghai can be classified as lower level in China. As described by Martin-vide (2004), precipitation CI can be used to determine the relative impact of different classes of daily precipitation and to evaluate the weight of the largest daily event in the total precipitation value (Coscarelli and Caloiero 2012; Shi et al. 2014). The structure of daily precipitation events shown in Fig. 4b explains the lower level of CI in Qinghai very well. The occurrence of daily precipitation with intensity of 0.1–5 mm is 79.1 % with the fractional contribution being 37.4 %, which indicating light precipitation events are prevalent in this province and heavy precipitation events are very scarce. Precipitation

changes in China are controlled mainly by the East Asian monsoons (Zhang et al. 2011). East Asian summer monsoon loses much of its moisture by the time it reaches the northwestern China. As a result, the frequency of heavy precipitation events decreases from southeast toward northwest throughout the country. Overall, the lower level of precipitation CI is consistent with the fewer heavy precipitation events in Qinghai.

According to Zhang et al. (2009), the precipitation CI has been calculated for each year and then its possible trends have been detected for each station using the MK test. Among 28 stations, the 21 CI series present negative trends, while the eight series present significant increasing trends (Fig. 4a). This indicates that the daily precipitation heterogeneity in Qinghai province is declining. Figure 5a shows that the positive correlation between precipitation CI and occurrence of daily precipitation events with intensity of ≤ 0.9 mm is significant. The negative correlation between precipitation CI and occurrence of daily precipitation events with intensity of 1–9.9 mm is also significant. Therefore, daily precipitation heterogeneity over Qinghai is

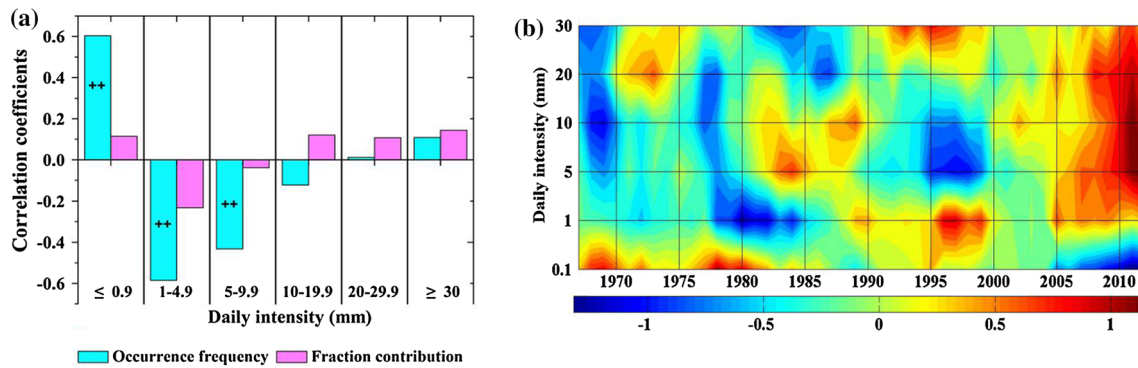


Fig. 5 **a** (Left panel) Correlation between multi-year average CI and daily precipitation events with different intensities at the scale of entire province (++) means Significant at the 0.01 level); **b** (Right

panel) temporal evolution in the normalized anomalies of occurrence frequency of daily precipitation events with different intensities across Qinghai

dominated by the daily precipitation events with low intensity. Figure 5b illustrates the temporal evolutions of occurrence frequency of daily precipitation with different intensity. Before analysis, the occurrences were standardized and then the 5-year moving average was computed (Zolina et al. 2010). Obviously, after the 1990s, a decreasing tendency can be observed for the occurrence of daily precipitation event with intensity of ≤ 0.9 mm. This abrupt change of extremely light precipitation event may be the main reason for the decrease of CI.

4.3 Spatial and temporal patterns of DS

The DS may help us to better recognize the dryness impact. Figure 6a–e displays the averaged annual number of DS with different length. As described by Fig. 6a–c, the lower values of NvsDS, NsDS and NmDS can be mainly found in northwest Qinghai. In contrast, the northwestern area presents higher values in NIDS and NvIDS. As a result, the northwestern area could be classified as the driest area in Qinghai. Other indices such as MLDS, MDS, total days of extreme DSs (DDS95) also supported the conclusions that intensity and extremes of DSs are found to be higher over the northwestern area (Fig. 6f–h). These outcomes are in agreement with the previous results, which found the averaged annual precipitation was less in north Qinghai, especially in the northwestern area (Bai et al. 2013). It should be noted that the contribution of 20 % driest spells to the total dry days (CDS20) are larger than 58.3 % (Fig. 6i), which means that the dry days mainly concentrate in a few driest spells and the drought risk are very high across Qinghai. The spatial patterns of DS indices in Qinghai are directly affected by its complex geomorphic and topographic characteristics. For instance, it is flanked by the Qilian Mountains on the north and Tanggula Mountains on the south, and Kunlun Mountains run across the central portion of this province (Liu et al. 2013). These may cause the moisture to

reach the northwestern areas difficultly, and the droughts are more serious in northwest Qinghai.

Identifying changes in the trend of the characteristics of DSs as well as the persistency of dry days will provide useful information in predicting future climatic events since these variables are closely related to extreme weather events such as drought and haze (Deni et al. 2010). The MK test is also used to test any trend in the DS indices, and Fig. 6 shows the spatial distribution of trends. Our results indicate remarkable differences among the stations with negative and positive precipitation trends for different indices. For example, more than half of stations are dominated by increasing NvsDS, NsDS, NmDS and NIDS. Especially there are 24 stations characterized by increasing NvsDS, accounting for 86 % of the total number of stations and 7 out of 24 are characterized by significant increasing NvsDS. Conversely, more than half of stations display decreasing trends in NvIDS, MLDS, MDS, DDS95 and CDS20. Noticeably, there are 25 stations characterized by decreasing MLDS, accounting for 89 % of the total number of stations and 11 out of 25 are characterized by significant decreasing MLDS. All these suggest that frequency, intensity and structure of DSs in Qinghai are changing. As described by Fig. 3, the rainy days in spring and winter display positive trends, whereas the rainy days in summer and autumn display negative trends. The seasonal changes of rainy days may directly result in the changes of DSs. It is worth mentioning that the number of very longer DSs, MLDSs, total days of extreme DSs within Qinghai province are generally in a decreasing tendency, which implies the alleviation of the risk of drought induced by DSs to some extent.

5 Discussion

The analysis of precipitation concentration is extremely important because of its high impact on environmental

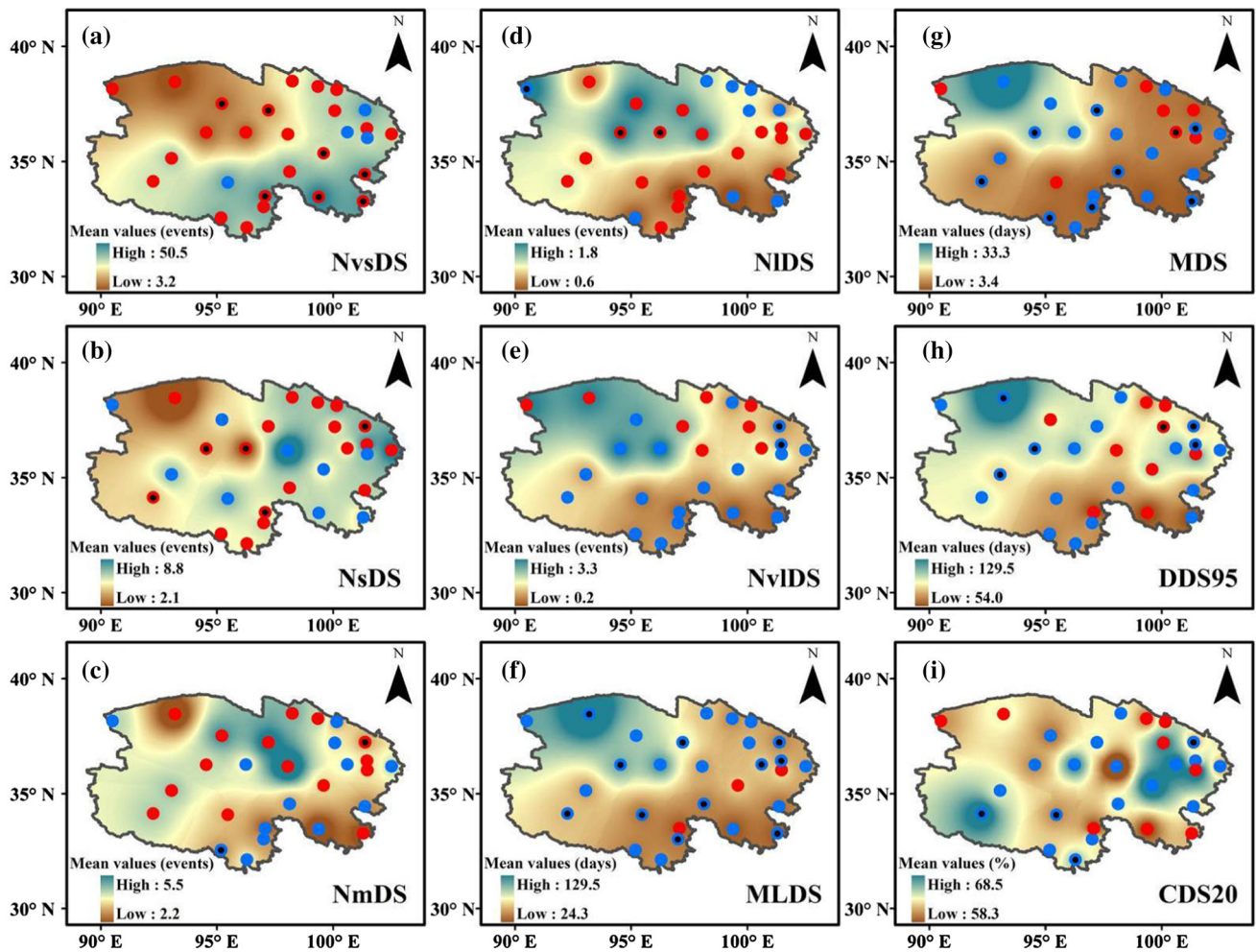


Fig. 6 Long-term mean values and trends of nine DS indices of Qinghai during 1963–2012 (Blue circles denote decreasing trends; red circles denote increasing trends; circles with a black dot show significant trends detected by MK test at the 10 % significance level)

phenomena such as floods and droughts and on water management. The PCI of Qinghai ranges between 15.5 and 35.4, which are much larger than PCI values of 17.1–20.5 in the Huai River Basin (Shi et al. 2014). The precipitation CI values in this study area (ranging from 0.58 to 0.65) are lower than those of the Huai River basin (Shi et al. 2014) and much lower than those of the Pearl River basin (Zhang et al. 2009). Different climatic systems may be considered as the important reason for the different levels of precipitation concentration. Qinghai has a plateau continental climate. Comparatively, Huai River basin is situated in the transition zone between the northern subtropical region and the southern warm temperature zone. The Pearl River basin of southeast China is characterized by monsoon climate. Moreover, the Pearl River basin often receives typhoon convective precipitations with extremely high rainfall event totaling over one or more days, leading to higher CI values in China.

As shown in the Figs. 2, 3 and 6, this province is dominated by an evident wet tendency during dry season, which is reflected mainly by decreasing tendencies of PCI and extreme DSs. Large-scale atmospheric circulations can be responsible for the changes of precipitation indices. Moisture transfer in Qinghai is characterized by the marked seasonal changes, mainly from the westerly winds in winter and spring to the monsoonal moisture originating from the Bay of Bengal and the South China Sea in summer, and the moisture is mainly obtained from the western Pacific Ocean in autumn (Ning et al. 2012). The recent 50 years have witnessed positive anomalies of precipitation in the Qinghai province during dry season, which may be a result of the anomalies of Westerly Circulation (Deng et al. 2014). Both an enhanced anticyclonic circulation centered on Lake Baikal and Mongolia (focused near 40°N and 110°E) and an anomalous cyclonic circulation near 50°N and 50°E have developed over Europe in winter and spring,

and the differences between anticyclonic circulation and cyclonic circulation over the Eurasian continent have been strengthened, suggesting an enhanced westerly during 1986–2008 as compared to 1961–1985 (Li et al. 2012). This, in turn, has weakened the southern extent of the winter monsoon, limited its southward extension and decreased incursions of colder air (You et al. 2011). Consequently, the water vapor flux brought by westerly circulation is characterized by an increasing tendency after 1980s. These may explain the increase of precipitation in Qinghai during winter and spring.

As shown in Fig. 4, the daily precipitation heterogeneity in this province is declining, which is reflected by decreasing tendencies of precipitation CI. This is mainly caused by the decrease of light precipitation events. Not just in Qinghai, the decreasing frequency of light rainfall days can be found over China (Huang and Wen 2013). As evidence of a possible influence of aerosols on precipitation frequency, Choi et al. (2008) reveal that, on the time scale of a few days, aerosol concentration is negatively correlated with the frequency of light rainfall days. A recent study has demonstrated very weak relationships between large-scale moisture transport and light rain in China, and suggests that the significantly increased aerosol concentrations produced by air pollution are at least partly responsible for the decreased light rain events observed in China over the past 50 years (Qian et al. 2009). Another possible cause of the decreasing frequency of light precipitation events is the decline in cloud cover. Fu et al. (2008) find that the decreasing trend of light rainfall days corresponds to the increasing trend of temperature in China, and they suggest that higher temperatures could increase the condensation height of precipitable clouds and reduce cloud amount so that light rainfall days are in turn reduced. In addition, the temporal pattern of light precipitation events in China is similar to those observed for solar irradiance, suggesting that the declines in solar irradiance may have contributed to the abrupt decrease of light precipitation events across China (Liu et al. 2011). In general, the mechanisms for changes of light precipitation events are highly complex, further investigation is needed to explore these physical processes in detail.

6 Conclusions

In this study, the spatial and temporal characteristics of changes in precipitation concentration and DS during 1963–2012 in Qinghai Province were explored. The main results are summarized as follows:

- (1) Two precipitation concentration indices were studied. For PCI, most of Qinghai is dominated by an irregular distribution of monthly precipitation. When it comes to CI, the daily rainfall heterogeneity in this province is much lower than any other regions in China. The decreasing tendency is detected in both PCI and CI in Qinghai, which indicating that weakening uneven distribution of rainfall may reduce difficulty in drought prevention and water resources utilization for the reservoirs.
- (2) Nine DS indices were analyzed. The spatial distribution of DS indices seems to indicate that the northwestern area is much drier than other areas. According to temporal analysis by using the MK test, the DS indices such as NvIDS, MLDS, MDS, DDS95 and CDS20 are dominated by the decreasing tendency. This means that the drought condition is allayed to some extent. In this case, the agriculture activities and water resource management in Qinghai should be well organized based on the new phenomenon in the changing climate.

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