Spatial-temporal Variation of Precipitation Concentration Degree and Precipitation Concentration Period in Gansu Province in Recent 50 Years

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Abstract. Inhomogeneity is the inherent attribute of precipitation and is usually an important factor affecting the occurrence of hydrological disasters such as floods and debris flows. Based on the monthly precipitation data of 27 national meteorological stations in the past 50 years, the spatial and temporal distribution characteristics of precipitation concentration degree (PCD) and precipitation concentration period (PCP) in Gansu Province were assessed in this study. The results indicated that: (a) the annual precipitation had distinct regional differences (annual average values were between 43.3-605.4 mm) and strong inter-annual fluctuations (coefficient of variation was usually above 0.20, some up to 0.40-0.45); (b) the main range of PCD was from 0.52 to 0.67, with significantly reduced inter-annual fluctuation and a long-term trend of gradual decrease; (c) the spatial-temporal variation of PCP was generally small, mainly concentrated in 192.8°-205.0° (mid-late July), and showed a slightly advanced variation tendency. Under the overall background of warming and wetting, Gansu Province presents evolution characteristics of PCD weakening and PCP advancing, and the formation mechanism and potential effects of this phenomenon require further attention.

1. Introduction
In the context of climate change, the global hydrological cycle is undergoing many changes [1,2]. These transitions are particularly prominent in the arid and semi-arid regions, and profoundly affect the function and stability of their terrestrial ecosystems [3-5]. In order to guarantee the sustainable development of social-economy and the health of ecosystems, it is necessary to objectively grasp the impact degree and mechanism of climate change on local hydrological elements.

As is well known, precipitation is not only the key input factor in the hydrological process, but also the direct influence element of floods, debris flows and other hydrological disasters. Therefore, evolution characteristics of precipitation have always been an essential content in the study of climate change and its impact, and the inhomogeneity is usually one of the focuses of attention [6-8]. Among them, the method of precipitation concentration degree (PCD) and precipitation concentration period (PCP) has been extensively used and encouraged the emergence of a large number of excellent results. Depending on the daily precipitation measurements recorded at 68 meteorological stations, Yang et al. found that PCD values of the Qinghai-Tibet Plateau are basically between 0.4 and 0.8 during 1967-2008, while PCP is mainly within the 36th-41st pentads [9]. Field observation data of the upper Shule...
River revealed that PCD of the alpine zone are above 0.71 from 2009 to 2015, with a maximum up to 0.83. PCP is likewise relatively stable, occurring in the 37th-41st pentads [10]. In the western plain of Jilin Province, PCP range from early July to late July, and PCD decrease by linear function, indicating that the precipitation exhibit a trend of balanced distribution [11]. By investigating the nonuniform variations of precipitation across China over the period 1960-2015, Zhao et al. confirmed PCD and PCP experience decreasing trends, indicating that annual feature of precipitation is changing [12]. In addition, compared with other geographical factors, longitude is the most significant variable that governs the spatial distribution and variations in annual precipitation and the precipitation concentration indices [13].

Gansu province, located at the intersection of the Qinghai-Tibet Plateau, the Mongolian Plateau and the Loess Plateau, is an important component of the arid and semi-arid regions in northwest China. In recent years, with the strengthening of ecological environment protection in the Qilian Mountains and the Yellow River basin, the research on climate change and hydrological response has made considerable progress [14,15]. However, few studies have investigated the variations of precipitation inhomogeneity. Meanwhile, the floods, debris flows and other hydrological disasters in mountainous areas as well as urban waterlogging problems have become increasingly conspicuous [16,17]. For these reasons, the spatial-temporal variation of PCD and PCP in Gansu Province was evaluated in this paper. It is expected that statistical characteristics of precipitation inhomogeneity can play important roles not only in flood and drought risk assessments but also in water resource management.

2. Materials and Methods

2.1. Study Area
Gansu Province is situated in the northwest of China, with a total area of 45.4×10³ km². Geographical location is between 92°13'-108°46' E and 32°31'-42°57' N (Figure 1). The terrain is long and narrow, exceeding 1600 km in the east-west direction, less than 550 km in the north-south direction. Due to the complex and varied landforms, the altitude difference is very great, ranging from 618 to 5508 m. Therefore, the climate types of Gansu Province are rich, including at least semi-humid, semi-arid and arid regions from southeast to northwest. The observation data since 1970 show that the annual average precipitation is between 43.3-605.4 mm, with the maximum and the minimum are 828.2 mm and 11.6 mm, respectively.

![Figure 1. Distribution of 27 national meteorological stations in Gansu Province.](image)

2.2. Data Acquisition
The observation data sets of all national meteorological stations in Gansu Province can be downloaded from the China Meteorological Data Network (http://data.cma.cn), but their precipitation data are not consistent in terms of starting time, update rate, data missing and other aspects.
Considering the timeliness and consistency of the observation data, 24 weather stations with complete data from 1970 to 2019 were firstly identified as the research objects. Then, in order to make up for the lack of data in the extremely arid climate regions, three additional stations (Anxi, Dunhuang and Yumen) with observation period during 1970-2017 were added. Therefore, a total of 27 national meteorological stations as showed in Figure 1 were selected to analyze the spatial-temporal variation of PCD and PCP in Gansu Province. The selected stations are located at altitudes between 1079 and 3471 m. The stations with 78% are located in lower part of Gansu Province below 2000 m. Only 7% (15%) of the stations are at altitudes higher than 3000 m (from 2000 to 3000 m). The results of annual precipitation, PCD and PCP were all calculated by monthly precipitation.

2.3. Methods
The PCD and the PCP are two standard statistical parameters based on vector analysis, which can be defined to describe the temporal distribution pattern of precipitation. The PCD can reflect the precipitation concentration level during certain periods in a year. The PCP, as the azimuth of a composite vector, indicates when the maximum precipitation occurs. They can be defined as below:

\[
PCD_i = \sqrt{\frac{R_x^2 + R_y^2}{R_i}}
\]

\[
PCP_i = \arctan\left(\frac{R_y}{R_x}\right)
\]

\[
R_x = \sum_{j=1}^{12} r_{ij} \times \sin \theta_j
\]

\[
R_y = \sum_{j=1}^{12} r_{ij} \times \cos \theta_j
\]

Where \(i\) is the year (\(i = 1970, 1971, \ldots, 2019\)), and \(R_i\) stands for the annual precipitation in the \(i\)th year. \(j\) is the month (\(j = 1, 2, \ldots, 12\)). \(\theta_j\) represents the corresponding azimuth angle of the \(j\)th month, while the year can be seen as 360°. \(r_{ij}\) denotes the precipitation of the \(j\)th month in the \(i\)th year. \(PCD_i\) is the precipitation concentration degree in the \(i\)th year, and the range of values is from 0 to 1. If annual precipitation occurs on a specific month, the maximum value (1) of \(PCD\), can be obtained. If annual precipitation is evenly distributed, the figure can reach its minimum value (0). \(PCP\), represents the month in which the annual precipitation in the \(i\)th year occurs. Detailed calculating methods and theories can be found in a paper written by Li [18].

3. Results and Discussion

3.1. Basic Characteristics of Annual Precipitation
In order to reveal the spatial-temporal distribution mechanism of PCD and PCP in Gansu Province, it is necessary and essential to analyze the basic characteristics of precipitation. Therefore, the mean values and coefficient of variation (Cv) of annual precipitation were calculated for all of 27 weather stations since 1970 (Figure 2). Obviously, the regional difference of annual precipitation in Gansu Province was prominent, with a maximum value as high as 605.4 mm (Maqu) and a minimum value of only 43.3 mm (Dunhuang). In terms of annual average precipitation, nearly half (44%) of the weather stations were positioned in the semi-humid regions, while the proportions of the arid and semi-arid regions were 37% and 19%, respectively.

In addition to the complex and changeable climate region, the interannual fluctuation was generally strong, which was another typical feature of precipitation in Gansu Province. As shown in Figure 2, the Cv of annual precipitation was mainly concentrated in 0.20-0.45, and only a few stations (Maqu and Hezuo) in the semi-humid regions were lower than 0.15. Furthermore, the negative correlation between the Cv and annual average precipitation was clear and can be described by a linear equation (\(R^2=0.70, p < 0.001\)). Meanwhile, the evolutionary trend of the overall increase in annual precipitation is also worthy of attention. Table 1 list the statistical results of annual precipitation changes at representative stations during 1970-2019. It can be found that although the direction and rate of
evolution are not consistent, there are more stations with increased precipitation, and their significance is generally stronger. For example, the annual precipitation in Yongchang, Wushaoling and Jiuquan increased obviously, with the rates reaching 12.6 mm/10a (statistically significant at the 99% confidence level), 16.0 mm/10a (statistically significant at the 95% confidence level) and 6.4 mm/10a (very close to statistically significant at the 95% confidence level), respectively. Based on the above results, the annual precipitation in Gansu Province has the general characteristics of large spatial difference, strong inter-annual fluctuation and prominent wetting.

![Figure 2. Coefficient of variation and mean values of annual precipitation in Gansu Province since 1970.](image)

**Table 1.** Evolutionary characteristics of annual precipitation in representative weather stations during 1970-2019.

| Station    | Linear Function | R²   | p         |
|------------|-----------------|------|-----------|
| Yongchang  | y = 1.2642x - 2309.2 | 0.1748 | < 0.01    |
| Wushaoling | y = 1.6002x - 2773.3 | 0.0979 | < 0.05    |
| Jiuquan    | y = 0.6388x - 1180.1 | 0.0707 | ≈0.05     |
| Mazongshan | y = -0.4583x + 986.3 | 0.0564 | < 0.10    |
| Huining    | y = -1.2052x + 2789.1 | 0.0526 | ≈0.10     |
| Huanxian   | y = 1.7104x - 2987.9 | 0.0484 | ≈0.10     |
| Lintao     | y = -1.5102x + 3526.8 | 0.0477 | ≈0.10     |
| Wuwei      | y = 1.7104x - 2987.9 | 0.0472 | ≈0.10     |
| Jingtai    | y = 0.8344x - 1472.9 | 0.0466 | ≈0.10     |

3.2. Spatial and Temporal Variation of PCD

Figure 3 displays the mean values and inter-annual variation of PCD at all 27 national meteorological stations since 1970. Compared with the annual precipitation, the regional difference of PCD decreased sharply, and the average value only fluctuated slightly in the range from 0.52 (Tianshui) to 0.67 (Mazongshan). In the meantime, the relationship between PCD and annual precipitation is more suitable to be expressed as a quadratic function equation (a < 0, R² = 0.19, p < 0.02) rather than a linear function (a < 0, R² = 0.11, p < 0.10). Thus it can be seen that the concentration degree of annual precipitation distribution in Gansu Province is roughly similar, usually at a medium level, and has a spatial variation trend of weakening with the increase of annual precipitation.
Temporal distribution characteristics of PCD, especially its long-term evolutionary trend, also need to be investigated in depth. The calculation results indicate that inter-annual distribution of PCD was basically stable, with Cv of most stations less than 0.15 and reaching 0.22-0.32 only in extremely arid climate regions. As can be seen from Table 2, evolutionary direction of PCD tends to be consistent, except for individual stations that are difficult to judge based on existing data. Among them, the weakening of PCD was most obvious in Wushaoling, Gaotai and Anxi, with the rates reaching 0.13/100a (statistically significant at the 99% confidence level), 0.25/100a (statistically significant at the 95% confidence level) and 0.35/100a (statistically significant at the 95% confidence level), respectively. Consequently, although the inter-annual variations of PCD in Gansu Province are usually small, the long-term evolutionary process of PCD decreasing gradually cannot be ignored.

3.3. Spatial and Temporal Variation of PCP

Similarly, the mean values and inter-annual variation of PCP at all 27 national meteorological stations since 1970 are depicted in Figure 4. Combining the results of the aforementioned two indicators (Figure 2 and Figure 3), it can be confirmed that the regional and inter-annual differences of PCP are the smallest. The PCP of each station was basically concentrated in 192.8°-205.0° (mid-late July), and only a few years can be lower than 180° (June and before) or higher than 210° (August and after). In terms of Cv, only some stations in arid climate region (0.14-0.16) are higher, while others are between 0.04 and 0.12. Additionally, the positive correlation between PCP and annual precipitation can be described as a linear function ($R^2=0.18$, $p < 0.01$), and the law becomes more and more intense as it gets closer to the arid climate area (from Dunhuang to Jingtai, $R^2=0.73$, $p < 0.001$). Although PCP is relatively stable, its long-term evolutionary trend also needs to be alerted (Table 3). First of all, the evolution direction of PCP has noticeable regional differences, and the number of stations that are advanced or delayed is basically equal. Secondly, judging from the significance, the tendency of PCP in advance is more dominant. For instance, rates of PCP advancing in Huaijiajing and Huining were 1.7 days /10a and 1.9 days /10a respectively, which were both very close to statistically significant at

![Figure 3. Inter-annual fluctuation and regional variation of PCD. Error bars represent one standard deviation.](image-url)
the 95% confidence level. These data indicate that the spatial and temporal distribution of PCP in Gansu Province remains relatively stable, mainly concentrated in the middle and late July. However, the assessment of PCP evolutionary trend (especially advancing) and the attribution of regional differences still needs to be focused on.

![Figure 4](image)

**Figure 4.** As in Figure 3, but for PCP (unit: degree in direction).

**Table 3.** As in Table 1, but for PCP.

| Station   | Linear Function | R²   | p     |
|-----------|-----------------|------|-------|
| Huajialing| \( y = -0.1717x + 541.1 \) | 0.0396 | <0.10 |
| Huining   | \( y = -0.1915x + 580.9 \) | 0.0349 | <0.10 |
| Yongchang | \( y = -0.1522x + 504.9 \) | 0.0244 | > 0.10 |
| Huanxian  | \( y = 0.1325x - 59.3 \)   | 0.0152 | > 0.10 |
| Minqin    | \( y = -0.1503x + 504.0 \) | 0.0148 | > 0.10 |
| Wushaoling| \( y = 0.0668x + 66.6 \)   | 0.0121 | > 0.10 |

In summary, under the overall background of warming and wetting, the precipitation in Gansu Province presents the evolutionary trend with PCD weakening and PCP advancing as the main characteristics. These changes are intertwined, indicating that the rainy season in Gansu Province is likely to occur ahead of time, except for the increase in precipitation. What role this phenomenon plays in the process of increasing hydrological disasters such as floods and debris flows is worthy of further discussion. The mechanism of action is inferred as follows: the early occurrence of the rainy season means lower soil temperature, weaker actual evapotranspiration and higher soil water content, which ultimately lead to more precipitation being converted into surface runoff. Of course, changes of single precipitation process, extreme precipitation events and other correlated factors must be also taken some influence. But the answers to these scientific questions can only depend on more detailed meteorological data and subsequent in-depth analysis.

### 4. Conclusions

According to the monthly precipitation data of 27 national meteorological stations since 1970, this paper preliminarily revealed the spatial-temporal variation characteristics of PCD and PCP in Gansu Province. The major results are summarized as follows: Firstly, the annual precipitation exhibited the overall characteristics of distinct spatial differences, strong inter-annual fluctuations and prominent wetting. Secondly, PCD had a spatial variation of weakening with the increase of annual precipitation and a long-term evolutionary trend of decreasing gradually. Finally, PCP was mainly concentrated in mid-late July, and showed a slightly advanced variation tendency. In the context of warming and wetting, Gansu Province presents evolutionary characteristics of PCD weakening and PCP advancing, and the formation mechanism and potential effects of this phenomenon require further attention.
5. Acknowledgments

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