Precipitation changes in the mid-latitudes of the Chinese mainland during 1960-2014 (postprint)

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Abstract

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Full Text

Preamble

Precipitation Changes in the Mid-Latitudes of the Chinese Mainland During 1960-2014

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Abstract: Based on daily precipitation data from 163 meteorological stations, this study investigated precipitation changes in the mid-latitudes of the Chinese mainland (MCM) during 1960-2014 using the climatic trend coefficient, least-squared regression analysis, and a non-parametric Mann-Kendall test. According to the effects of the East Asian summer monsoon on the MCM and the climatic trend coefficient of annual precipitation during 1960-2014, we divided the MCM into western and eastern regions. The western MCM was further subdivided into western MCM1 and western MCM2 based on differential monsoonal influence. The main results were as follows: (1) During the last four decades of the 20th century, area-averaged annual precipitation exhibited a significant increasing trend in the western MCM but a slight decreasing trend in the eastern MCM, manifesting a seesaw pattern. However, in the 21st century, area-averaged annual precipitation displayed a significant increasing trend in both western and eastern MCM. (2) The trend in area-averaged seasonal precipitation during 1960-2014 in the western MCM was consistent with that in the eastern MCM in winter and spring. However, the trend in area-averaged summer precipitation during 1960-2014 displayed a seesaw pattern between western and eastern MCM. (3) On an annual basis, both rainstorm and heavy rain trends exhibited a seesaw pattern between western and eastern MCM. (4) Precipitation intensity in rainstorms, heavy rain, and moderate rain contributed more to changes in total precipitation than did precipitation frequency. These results improve our understanding of precipitation trends and regional differences across the MCM, providing valuable insights for flood disaster management and water resource protection.

Keywords: precipitation changes; mid-latitudes of the Chinese mainland; seesaw pattern; rainy days; precipitation intensity; precipitation frequency

1 Introduction

Under the background of global warming, global precipitation quantity and patterns have changed. Precipitation increased by 0.5%-1.0% per decade over most middle to high latitudes of the Northern Hemisphere continents (IPCC, 2001). However, the increasing trend in surface air temperature has slowed since the late 1990s, leading to claims of a global warming hiatus. In this context, how precipitation in China—particularly in the mid-latitudes of the Chinese mainland (MCM)—has responded to this warming hiatus remains unresolved.

With respect to precipitation changes in China, studies have been conducted at both national and regional scales (Zhai et al., 1999; Gemmer et al., 2004; Fu et al., 2008; Zhang et al., 2012; Meng et al., 2013; Liu et al., 2015). Liu et al. (2005) examined spatiotemporal variations in precipitation across China during 1960-2000, finding that precipitation amount increased by 2% while precipitation event frequency decreased by 10%. Wang et al. (2004) studied inter-decadal variability of precipitation in China since the 1880s, indicating that national-scale mean precipitation depended primarily on precipitation over eastern China. Wang and Zhou (2005) investigated trends in annual and seasonal mean precipitation from 1961 to 2001, revealing significant increases in southwestern, northwestern, and eastern China, but significant decreases in central, northern, and northeastern regions. The increasing trend in northwestern China occurred across all seasons.

Northwestern China has a dry climate and is located far from oceanic influence. Alongside rising air temperatures, precipitation in this region increased significantly during the last 30 years of the 20th century (Zhu and Chang, 2011; Meng et al., 2013). Concurrently, under the effects of anthropogenic climate change and an enhanced water cycle, precipitation, glacial meltwater, river runoff, air temperature, inland lake levels, and flood disaster frequency all increased continuously from the 1980s to the 2000s (Shi et al., 2007). By investigating the relationship between precipitation and evaporation, Shi et al. (2003) found that northwestern China’ s climate shifted from warm-dry to warm-wet in 1987. Li et al. (2003) forecasted that this warm-dry to warm-humid transition would continue, particularly in Xinjiang Uygur Autonomous Region, western Hexi Corridor, Qilian Mountains, and parts of Qinghai Province.

Because there are profound regional differences, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) emphasized the need for exhaustive sub-regional studies, especially for transitional climate zones. The MCM has a typical transitional climate, ranging from continental in the west to temperate monsoon in the east. The East Asian summer monsoon substantially contributes to precipitation in the eastern MCM but has little effect on the western MCM. Therefore, to take early action preventing water scarcity in arid regions and mitigating flood disasters in humid regions, it is essential to explore precipitation changes and their causes in the MCM. From this perspective, comparative investigation of precipitation changes between western and eastern MCM is necessary.

Additionally, over a decade has passed since Shi et al.’ s (2003) climate change study in northwestern China. There is a need to determine whether precipitation in this region has continued increasing in recent years, to investigate precipitation characteristics in the eastern MCM, and to examine the relationship of precipitation changes between western and eastern MCM. This study addresses these questions through follow-up analysis of precipitation changes in northwestern China and initial investigation of precipitation changes in the eastern MCM, including inter-comparison between the two regions. This is not only useful for flood disaster management and mitigation but also beneficial for water resource protection across the MCM.

It should also be noted that atmospheric water content increases with temperature, meaning higher temperatures potentially produce heavier precipitation (Kundzewicz, 2005). Several studies have shown that global warming could enhance precipitation intensity and alter precipitation extremes (Trenberth, 1998; Allen and Ingram, 2002; Semenov and Bengtsson, 2002; Trenberth et al., 2003). Station data from middle to high latitudes of the Northern Hemisphere indicate increased frequency of heavy precipitation events during the second half of the 20th century (IPCC, 2001). The IPCC Fourth Assessment Report further indicated that heavy precipitation events would very likely increase in China.

Wang and Zhou (2005) analyzed observed trends in extreme precipitation events from 1961 to 2001, showing that patterns in extreme daily precipitation trends were similar to those for mean annual and seasonal precipitation, except in northwestern China where most areas displayed increasing trends only in summer. Liu et al. (2015) studied extreme precipitation trends in eastern China using urban and rural station data during 1955-2011, indicating significant increases in heavy precipitation and decreases in light rain at both rural and urban stations. However, trends in extreme precipitation event frequency in the MCM have received little attention, with most studies focusing on summer. Thus, comparative investigation of trends across different precipitation grades—from light rain to rainstorms—in different MCM areas is necessary.

The objective of this study was to identify relationships of precipitation changes between western and eastern MCM, address whether precipitation in the western MCM has continued increasing in the early 21st century, and examine how precipitation in the eastern MCM changed during 1960-2014. Changes in different precipitation grades were also analyzed. These results provide a reference for policymakers to prevent water scarcity in arid regions and mitigate flood disasters in humid regions, while improving understanding of precipitation trends and regional differences across the MCM.

2.1 Study Area

The MCM (35°-45°N, 75°-120°E; Fig. 1 [Figure 1: see original paper]) was selected as the study area, covering both the western MCM (mainly affected by westerlies) and the eastern MCM (primarily influenced by the East Asian summer monsoon). The boundary between these two regions is the Helan Mountains. Because the Hexi Corridor area in the eastern part of the western MCM is periodically affected by the East Asian summer monsoon, while the Xinjiang area in the western part is not, the western MCM can be further divided into western MCM1 (Xinjiang area) and western MCM2 (Hexi Corridor area).

There are 163 meteorological stations in the MCM with approximately even spatial coverage. The western MCM1 contains 37 stations, the western MCM2 contains 32 stations, and the eastern MCM contains 94 stations (Fig. 1). An increasing trend in annual precipitation was detected at all stations except one in the western MCM1, and at all stations except two in the western MCM2. In the eastern MCM, the pattern was more complex: 49 stations showed increasing trends while 35 showed decreasing trends, with both types distributed equally across the region.

In summer, abundant precipitation is generated in the eastern MCM under the concurrent effects of the East Asian summer monsoon, atmospheric wind field, geographical height, and the western Pacific Ocean subtropical high, while the western MCM receives relatively less precipitation due to minimal monsoonal impact. In winter, both western and eastern MCM experience dry, rainless conditions due to the East Asian winter monsoon and related synoptic climate systems.

2.2 Data

Precipitation data were obtained from the National Meteorological Information Center of the China Meteorological Administration (http://cdc.cma.gov.cn/index.jsp). Daily precipitation data from each station were available from 1 December 1959 to 28 February 2015. Data quality was controlled using a von Neumann ratio (N), cumulative deviations (Q/n-0.5 and R/n-0.5), and Bayesian procedures (U and A; Buishand, 1982; Maniak, 1997). The dataset passed these three tests at the 95% confidence level and was considered reliable.

Days with precipitation 0.1 mm were defined as rainy days, and daily precipitation totals were treated as precipitation events. According to CMA standards, observed daily precipitation (P) can be categorized into four intensity grades: light rain (0.1 P<10 mm/d), moderate rain (10 P<25 mm/d), heavy rain (25 P<50 mm/d), and rainstorms (P 50 mm/d).

Seasonal precipitation was calculated using standard season definitions: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Annual precipitation time series were constructed using data from January to December of each year. Area-averaged annual, seasonal, and monthly precipitation (and rainy days) were calculated by dividing totals from stations in each area by the number of stations in that area. Mean precipitation was calculated using records from the full 1960–2014 period.

2.3 Methodology

The non-dimensional climatic trend coefficient (rxt; Shi et al., 1995; Shi and Deng, 2000; Shi et al., 2003) was used to quantitatively depict precipitation variation in the MCM. This is defined as the correlation coefficient between an element’ s series and the natural number sequence 1, 2, 3, ···, n:

$$r_{xt} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(t_i - \bar{t})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(t_i - \bar{t})^2}}$$

where t is time in years, x_i is the element value in the ith year, $\bar{x}$ is the sample mean, and $\bar{t} = (n+1)/2$. A positive (or negative) r_{xt} indicates a linearly increasing (or decreasing) trend. Because r_{xt} is non-dimensional, its magnitude can be compared across different variables.

Precipitation changes were evaluated using simple linear regression analysis and a non-parametric Mann-Kendall (M-K) test (Kendall, 1938, 1975). The least-squared linear regression model was applied to estimate change intensities in mean precipitation, with the slope representing the rate of change per decade (Shen and Sheng, 2008). The non-parametric M-K test, a rank-based procedure, was used to detect non-linear trends. Confidence levels of 90%, 95%, and 99% were used as thresholds to classify trend significance; trends below the 90% level were not considered.

Precipitation changes can be attributed to changes in frequency, intensity, or a combination of both (Karl and Knight, 1998). Using CMA precipitation intensity classifications, we evaluated the proportion of total precipitation trends attributable to frequency versus intensity changes. The precipitation frequency component was calculated by determining mean precipitation amount per event (P_e) and the trend in precipitation frequency (b_f). The precipitation change related to frequency trends is defined as:

$$b_e = b_f \times P_e$$

where b_e is the trend component from precipitation frequency (mm/a). The intensity component was calculated as a residual:

$$b_i = b - b_e$$

where b_i is the trend component from precipitation intensity and b is the total precipitation trend (Karl and Knight, 1998).

Both precipitation trends at different timescales and inter-comparisons of precipitation changes across areas were analyzed using these methods.

3.1.1 Trends of Area-Averaged Annual Precipitation

Mean annual precipitation at individual stations in the MCM varied considerably, ranging from 14.0 mm (Turpan station in western MCM1, with a continental warm temperate desert climate) to 1025.9 mm (Taishan station in eastern MCM, with a continental warm temperate monsoon climate). The area-averaged annual precipitation during 1960–2014 was 107.9 mm over western MCM1, 180.2 mm over western MCM2, and 450.0 mm over eastern MCM. This west-to-east increase reflects different climate types between the regions.

Area-averaged annual precipitation during 1960–2014 in both western MCM1 and western MCM2 displayed significant increasing trends at the 99% confidence level, with rates of 13.6 and 10.5 mm/10a, respectively (Figs. 2a–d). Increasing precipitation intensity and frequency were responsible for these increases in western MCM1 and MCM2, respectively (Qian and Lin, 2005; Jia, 2012). As shown in Figure 2 [Figure 2: see original paper], regression line slopes for 1960-1999 were much greater than those for 1960-2014 in both areas. In eastern MCM, area-averaged annual precipitation showed a slight decline during 1960–1999 but a slight increase during 1960-2014 (Figs. 2e and f). The decrease during 1960-1999 may be attributed to a southward shift in the major component of East Asian summer monsoon circulation (Li et al., 2010).

Inter-annual variation of area-averaged annual precipitation during 1960–2014 was analyzed using the M-K test. A mutation point occurred in 1982 in the western MCM, with precipitation increasing dramatically afterward, passing the 95% confidence level (Fig. 3a [Figure 3: see original paper]). In contrast, no mutation point was detected in the eastern MCM during 1960–2014 (Fig. 3b), as precipitation decreases at 45 stations partially offset increases at 49 stations.

Close inspection of Figure 4 [Figure 4: see original paper] reveals that during the last four decades of the 20th century, area-averaged annual precipitation increased significantly in the western MCM while decreasing slightly in the eastern MCM, displaying a seesaw pattern. In the 21st century, both western and eastern MCM have shown significant increasing trends, exceeding the 90% confidence level. This indicates that the increasing precipitation trend has continued in the western MCM, while the eastern MCM' s seesaw pattern has converted to an increasing trend.

3.1.2 Trends of Area-Averaged Seasonal Precipitation

The non-parametric M-K test and least-squared linear regression model were used to analyze area-averaged seasonal precipitation trends in the MCM, revealing significant regional differences. In western MCM1, area-averaged seasonal precipitation during 1960–2014 displayed significant increasing trends at the 99% confidence level in all seasons, with maximum trend (4.0 mm/10a) in summer and minimum (2.9 mm/10a) in spring. In western MCM2, significant increasing trends at the 99% level were detected in winter and spring, and at the 95% level in summer and autumn, with maximum trend (3.7 mm/10a) in spring and minimum (1.0 mm/10a) in winter. In eastern MCM, area-averaged seasonal precipitation showed significant increasing trends at the 99% confidence level in winter and 95% in spring, with rates of 2.6 and 3.4 mm/10a, respectively, but a non-significant decreasing trend in summer (Table 2).

Overall, the trend in area-averaged seasonal precipitation during 1960–2014 in the western MCM was consistent with that in the eastern MCM in winter and spring, as both regions are concurrently affected by the East Asian winter monsoon and related synoptic climate systems during these seasons. However, the trend in area-averaged summer precipitation displayed a seesaw pattern between western and eastern MCM. The increasing trends in precipitation intensity and frequency may be responsible for summer precipitation increases in the western MCM (Qian and Lin, 2005; Jia, 2012), while the southward shift of the East Asian summer monsoon circulation major component could account for summer precipitation decreases in the eastern MCM (Li et al., 2010).

3.1.3 Trends of Area-Averaged Monthly Precipitation

Non-parametric M-K test results for area-averaged monthly precipitation during 1960–2014 revealed spatially different trends across MCM regions. As shown in Figure 5 [Figure 5: see original paper], significantly increasing trends at the 90%, 95%, and 99% confidence levels were conspicuous in January, February, March, and December across all three areas. In western MCM1 and MCM2, area-averaged monthly precipitation in all 12 months displayed increasing trends. In eastern MCM, area-averaged monthly precipitation showed significant increasing trends in January, February, March, May, June, and December, but significant decreasing trends in July and August (Fig. 5). These significant decreases in July and August further confirm the summer precipitation decline in eastern MCM and the seesaw pattern between western and eastern MCM in summer.

3.2 Comparison of Precipitation Changes on an Inter-Decadal Timescale

A comparative study of decadal precipitation changes between western and eastern MCM was conducted by analyzing decadal precipitation anomaly variations.

In western MCM1, decadal precipitation anomalies were negative from the 1960s to 1970s in all four seasons but positive from the 1980s to 2010-2014 (Table 3). In western MCM2, decadal precipitation anomaly signs matched those in western MCM1 in winter and spring, but exhibited irregular patterns in summer and autumn because this transitional climate region is periodically affected by the East Asian summer monsoon, whose advance and retreat largely determines rainy season timing. We conclude that conditions were relatively wetter after the 1980s in the western MCM (periods before and after the 1980s are treated as dry and wet epochs, respectively). In eastern MCM, decadal precipitation anomaly signs matched those in the western MCM in winter and spring, but were opposite to western MCM1 in summer, further confirming the seesaw pattern between western and eastern MCM in summer.

Decadal precipitation changes during 1960-2014 were most pronounced in western MCM1, followed by western MCM2. Moreover, in western MCM1, no seasonal variation occurred in the signs of decadal precipitation anomalies from the 1960s to 2010-2014. In response to global warming since the late 1980s, decadal precipitation in the western MCM increased significantly, especially in winter (Table 3).

As discussed above, precipitation changes on an inter-decadal timescale compared well with those on an inter-annual timescale in both western and eastern MCM.

3.3 Trends in Different Grades of Precipitation

Trends in different precipitation grades during 1960-2014 were analyzed using the non-parametric M-K test and least-squared linear regression model. Results revealed that on an annual basis, both rainstorm and heavy rain trends displayed opposite patterns in western and eastern MCM.

3.3.1 Trends in Different Grades of Annual Precipitation and Corresponding Rainy Days

On an annual basis, area-averaged annual precipitation comprised 64.1% light rain, 28.0% moderate rain, 7.2% heavy rain, and 0.7% rainstorms in western

MCM1. Corresponding figures were 58.1% light rain, 33.6% moderate rain, 7.4% heavy rain, and 0.9% rainstorms in western MCM2, and 30.9% light rain, 31.8% moderate rain, 22.2% heavy rain, and 15.1% rainstorms in eastern MCM. The percentage contribution of light rain to area-averaged annual precipitation decreased from west to east across the MCM, while contributions from moderate rain, heavy rain, and rainstorms increased west to east.

In western MCM1, a non-significant increasing trend in rainstorms occurred during 1960–2014 (Table 4), with regression slope indicating an increase of 0.15 mm/10a (Fig. 6a [Figure 6: see original paper]). A similar trend (0.02 mm/10a) was detected for rainstorms in western MCM2. Both heavy and moderate rain increased significantly at the 99% confidence level in western MCM1 (Table 4), with rates of 1.2 and 3.7 mm/10a, respectively (Figs. 6b and c). A significant increasing trend at the 99% confidence level was detected for moderate rain in western MCM2, with a rate of 3.5 mm/10a. Light rain in both western MCM1 and MCM2 displayed significantly increasing trends at the 99% confidence level, with rates of 8.4 (Fig. 6d) and 6.1 mm/10a, respectively. In eastern MCM, rainstorms and heavy rain exhibited decreasing trends, while moderate rain and light rain displayed increasing trends (Table 4).

Although rainstorms and heavy rain showed increasing trends in both western MCM1 and MCM2, they decreased in eastern MCM, displaying a seesaw pattern between western and eastern MCM. Additionally, for all precipitation types, variations in area-averaged annual rainy days were in good agreement with area-averaged annual precipitation in each region, indicating that rainy day number played an important role in precipitation changes (Table 4).

3.3.2 Trends in Different Grades of Seasonal Precipitation and Corresponding Rainy Days

Analysis of area-averaged seasonal amounts for different precipitation grades during 1960–2014 revealed differences among the three regions (Table 5). In western MCM1 and MCM2, area-averaged seasonal amounts of all precipitation types displayed increasing trends across all four seasons. In eastern MCM, similar increasing trends occurred only in winter and spring, while decreasing trends appeared in summer.

In western MCM1, heavy rain showed conspicuous increasing trends in spring, summer, and autumn at the 90%, 95%, and 95% confidence levels, respectively, with the largest rate (0.66 mm/10a) in summer. Both moderate rain and light rain displayed significant increasing trends at the 99% confidence level in all four seasons (Table 5). In western MCM2, heavy rain in summer showed a significant increasing trend at the 95% confidence level (0.88 mm/10a). Moderate rain displayed significant increasing trends in spring and summer (0.9 and 1.7 mm/10a, respectively). Light rain showed significant increasing trends at the 99% confidence level in spring, autumn, and winter, with maximum rate in spring (2.66 mm/10a). In eastern MCM, summer rainstorms exhibited a conspicuous decreasing trend at the 95% confidence level (-3.22 mm/10a) (Table 5). Heavy rain in spring displayed a significant increasing trend at the 95% confidence level (0.62 mm/10a). For all precipitation types, trends in area-averaged seasonal rainy days were consistent with those in area-averaged seasonal precipitation across all seasons and regions (Table 5).

For all precipitation types, the trend in area-averaged seasonal precipitation during 1960-2014 in the western MCM was consistent with that in the eastern MCM in winter and spring, as was the trend in area-averaged seasonal rainy days. However, both area-averaged summer precipitation and summer rainy days displayed a seesaw pattern between western and eastern MCM.

3.4 Impact of Precipitation Frequency and Intensity on Total Rainfall in Different Precipitation Categories

Changes in precipitation event frequency and intensity per event affect local precipitation. We investigated these changes for different precipitation grades. In western MCM1, increased intensity per rainstorm contributed more to total rainfall increase from rainstorms than increased frequency, with intensity accounting for 98.36% of the total increase. For heavy rain, intensity contributed 88.21% versus 11.79% from frequency. For moderate rain, intensity contributed 61.78% versus 38.22% from frequency. In contrast, for light rain, intensity contributed much less than frequency, accounting for only 10.19% of the total increase (Fig. 7a). In western MCM2, intensity and frequency contributions were similar to western MCM1 (Fig. 7b [Figure 7: see original paper]).

In eastern MCM, area-averaged annual rainstorms and heavy rain decreased while moderate rain and light rain increased. Intensity decrease accounted for 73.89% of the total rainstorm decrease, with frequency decrease contributing the remaining 26.11%. For heavy rain, 98.67% of the total decrease was due to intensity decrease, while decreased frequency accounted for only 1.33%. For moderate and light rain, intensity and frequency contributions to total increase were similar to those in western MCM (Fig. 7c). Thus, for precipitation grades from rainstorms to moderate rain, precipitation intensity contributed more to changes than frequency, while the opposite was true for light rain.

4 Conclusions

Analysis of daily precipitation data from 163 meteorological stations revealed that trends in area-averaged annual precipitation during 1960-1999 displayed a seesaw pattern between western and eastern MCM. In the 21st century, both western and eastern MCM have shown significant increases in area-averaged annual precipitation. More detailed conclusions are as follows.

The trends in area-averaged annual precipitation during 1960-2014 in both western MCM1 and MCM2 displayed significant increases, exceeding the 99% confidence level. The trend in area-averaged seasonal precipitation during 1960-2014 in the western MCM was consistent with that in the eastern MCM in winter and spring, as both regions are concurrently influenced by the East Asian winter monsoon during these seasons. However, the trend in area-averaged summer precipitation displayed a seesaw pattern between western and eastern MCM, attributable to differential effects of the East Asian summer monsoon. Rainy day number played an important role in precipitation changes.

At both annual and seasonal timescales, the trend in rainstorms during 1960-2014 displayed a seesaw pattern between western and eastern MCM, a pattern also apparent for heavy rain. For rainstorms, heavy rain, and moderate rain, precipitation intensity contributed more than frequency to changes, while frequency dominated changes in light rain.

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Note: Figure translations are in progress. See original paper for figures.