Abstract

We applied the Mann-Kendall (MK) test and Bayesian model to systematically explore trends and abrupt changes of the precipitation series in the Pearl River basin. The results showed that no significant trends were detected for annual precipitation and summer or winter precipitation totals. Significant negative trends were identified for the number of rainy days across the Pearl River basin; significant positive trends were observed regarding precipitation intensity (PI). In particular, the precipitation totals and frequencies of extremely high precipitation events are subject to significant positive trends. In addition, the number of extremely low precipitation events was also increasing significantly. Factors affecting the changes in precipitation patterns are the weakening Asian monsoon and consequently increasing moisture transport to Southern China and the Pearl River basin. In summary, the main findings of this study are: (1) increased precipitation variability and high-intensity rainfall was observed though rainy days and low-intensity rainfall have decreased, and (2) the amount of rainfall has changed little but its variability has increased over the time interval divided by change points. These finds indicate potentially increased risk for both agriculture and in locations subject to flooding, both urban and rural, across the Pearl River basin. Copyright © 2009 Royal Meteorological Society

Keywords: precipitation; China; Pearl River; Mann-Kendall trend test; change point detection; Bayesian model

1. Introduction

Precipitation variability in space and time has been affecting human societies over the world. Therefore, it is a judicious choice to obtain good knowledge of changes in magnitude and frequency of precipitation regimes, especially extreme precipitation events (Durrans and Kirby, 2004). Moreover, currently well-evidenced global warming is changing precipitation patterns worldwide in space and time. Higher average air temperatures result in higher evaporation rates, higher water vapor content, and consequently, an accelerated hydrological cycle (Menzel and Bürger, 2002). Furthermore, water means too much to human societies and nature which underscores the necessity of understanding how a changing climate could affect regional water supplies (Xu and Singh, 2004; Xu et al., 2006). Therefore, numerous studies on precipitation variability have been undertaken all over the world with various statistical procedures. Matsuyama et al. (2002) explored the spatial and temporal variations of precipitation in tropical South America from 1979 to 1998 using the rotated empirical orthogonal functions and the Lepage test. With the help of Mann-Kendall (MK) test, Becker et al. (2004, 2006) and Gemmer et al. (2004) found significant trends in monthly precipitation in the Yangtze River basin. Endo et al. (2005) detected long-term trends in summer precipitation, number of rainy days, and precipitation intensity (PI) from 1961 to 2000 in China, indicating significant positive trends of precipitation in summer and the number of rainy days in the Yangtze River basin. Wang and Zhou (2005) studied trends of annual and seasonal mean precipitation and extreme precipitation events in China during 1961–2001, showing that annual mean precipitation has increased significantly in Southwestern, Northwestern, and Eastern China and decreased significantly in Central, Northern and Northeastern China.

In light of the causes behind the observed phenomena, Ding and Chan (2005) suggested that the onset and intensity of the Asian monsoon play a crucial role in heat and moisture transport. Mao and Wu (2006) concluded that the intra-seasonal variations in the Yangtze rainfall are mainly determined by the coupling between the low-level relative vorticity and the upper-level divergence. Becker et al. (2004) related rainfall variability in the Yangtze basin to v-wind at
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the 700 hPa level over southern China, showing that the precipitation in the region not only depends on the monsoon intensity but also on the amount of water vapor.

The Pearl River is the second largest river in China in terms of streamflow. Approximately 80% of the total discharge occurs from April to September. Uneven spatial and temporal precipitation distribution, to a certain degree, negatively affects the effective human use of water resource. The Pearl River basin is a highly-developed region having the unshakable position in the economic development of China. It has been the fastest developing region in China since the country adopted the ‘open door and reform’ policy in the late 1970s. With thriving development of social economy within the Pearl River basin, the shortage of clean water due to pollution has the potential to deteriorate the water environment. The East River, a tributary of the Pearl River, is the main source of water supply for Shenzhen and Hong Kong. About 80% of Hong Kong’s annual water demands rely on water supply from the East River. Moreover, streamflow changes of the Pearl River directly affect the water environment (e.g., salty intrusion) of the Pearl River Delta. Given the fact that streamflow variability is directly connected to precipitation variability, it is evident that a good understanding of the latter in the Pearl River basin will be essential for fluvial water resource management. However, few thorough studies of precipitation changes within the Pearl River basin have been conducted so far. Dong (2006) analyzed potential correlations between extreme precipitation events and flood hazards in the Pearl River basin, showing the significant impact of extreme precipitation on floods. However several issues still remain unanswered. So far, no pertinent reports are available regarding (1) trends in the number of rainy days and related PI, (2) trends in extreme precipitation events as defined by certain thresholds, and (3) abrupt changes in PI and related statistical characteristics. All these aspects are considered to be important for fluvial water resource management and mitigation of floods or droughts. This is the major motivation for this study. Thus, the objectives of this study are (1) to explore trends in the number of rainy days, rainfall intensity; and (2) to detect the change points in the time series and associated statistical characteristics.

2. Study region and data

2.1. Study region

The Pearl River (97°39′E–117°18′E; 3°41′N–29°15′N) (Figure 1) is the third largest river in China with drainage area of 7.96 × 10^5 km^2 of which 4.42 × 10^5 km^2 is located in China. The Pearl River basin consists of three major rivers (PRWRC, 1991): Xijiang, Beijiang and Dongjiang. The largest of these three is the Xijiang, which comprises the Nanpanjiang, Hongshuihe, Qianjiang and Xijiang. The main tributaries are Beipanjiang, Liujiang, Yujiang and Guijiang (Figure 1). The total length of Xijiang is 2075 km with a drainage area of 353 120 km^2, accounting for 77.8% of the total Pearl River basin drainage area. The Beijiang is the second largest tributary of the Pearl

Figure 1. Location of the study region, the rain gauge stations and tributaries of the Pearl River.

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DOI: 10.1002/asl
Precipitation maxima in the Pearl River basin, China

Figure 2. Trends of (A) annual precipitation, (B) the number of rainy days, and (C) precipitation intensity within the Pearl River basin. The ○ indicates no significant trend, ▲ indicates significant positive trend and ▼ indicates significant negative trend at the >95% confidence level.

River with a length of 468 km and a drainage area of 46 710 km². The Dongjiang River is about 520 km long with a drainage area of 27 000 km², accounting for 6.6% of the total area of the Pearl River basin. The Pearl River basin is dominated by tropical and sub-tropical climate, which is characterized by abundant precipitation and generally high temperatures. The annual mean temperature is 14–22 °C; average annual humidity is 71–80%. The main precipitation occurs from April and September.

2.2. Data

The study is based on the analysis of daily precipitation data of 1951 to 2005 from 47 rain gauge stations in the Pearl River basin (Figure 1). The PI was defined as total precipitation during a time period divided by the number of rainy days (Zhang et al., 2008a).

APa = annual precipitation extremes which are exceeding the upper threshold;
APb = annual precipitation extremes which are falling below the lower threshold.

The extreme precipitation was defined as precipitation exceeding/falling below certain thresholds. The upper threshold is defined as the arithmetic mean of the time series plus 0.25 standard deviations. The lower threshold is defined as the arithmetic mean minus 0.25 standard deviations. This definition is based on the studies by Yoo (2006) who suggests that such an approach will facilitate data analysis of rainfall records which are potentially affected by abrupt changes. To facilitate the understanding of the various parameters we define the following shortcuts:
Figure 3. Annual extreme precipitation defined as precipitation exceeding mean $+ 0.25\text{std}$ (A, B, C) and falling below mean $- 0.25\text{std}$ (D, E, F). A and D: total amount of the annual extreme precipitation; B and E: number of days with precipitation exceeding/falling mean $\pm \text{std}$. C and F: precipitation intensity. The $\circ$ indicates no significant trend, ▲ indicates significant positive trend and ▼ indicates significant negative trend at the $>95\%$ confidence level.

Analogously we use SPa and SPb for summer precipitation extremes and WPa and WPb for winter precipitation extremes.

Due to the fact that the precipitation regime in the study region is characterized by two distinctive seasons (wet summers, dry winters) we analyzed trends for summer (June, July and August) and winter (December, January and February) separately.

Following the suggested link between Asian monsoon onset and rainfall variability (Ding and Chan, 2005) we explored the atmospheric circulation behind the precipitation changes in the Pearl River basin by studying the intensity of the south Asian monsoon based on the NECP/NCAR reanalysis data (http://www.cdc.noaa.gov). Following Qiao et al. (2002) we defined the region covering $20^\circ - 40^\circ\text{N}$ and $100^\circ - 140^\circ\text{E}$ as the Asian monsoon region. The intensity index of southwest monsoon is defined as $I_{sw} = \Sigma u_{sw}/n_{sw}$ and the southeast monsoon is $I_{se} = \Sigma u_{se}/n_{se}$, where $u_{sw}/u_{se}$ is the wind velocity of the south-west/south-east monsoon of each grid and $n_{sw}/n_{se}$ is the number of grid cells (Qiao et al., 2002). In addition we calculated the vertically integrated moisture budget based on the methods by Zhang et al. (2009).

3. Methodology

3.1. Trend test

The nonparametric MK trend test was applied to explore trends in the precipitation time series (Mann, 1945; Kendall, 1975). This test has the advantage of not requiring any distribution form for the data and has the similar power as its parametric competitors (Serrano et al., 1999). Therefore, it is highly recommended for general use by the World Meteorological Organization (Mitchell et al., 1966). In this test, the null hypothesis $H_0$ is that the deseasonalized data $(x_1, \ldots, x_n)$ are a sample of $n$ independent and identically distributed random variables (Yu et al., 1993). The alternative hypothesis $H_1$ of a two-sided test is that the distribution of $x_k$ and $x_j$ are not identical for all $k, j \leq n$ with $k \neq j$ (Kahya and Kalayci, 2004). The test statistic $S$ is computed with Equations (1) and (2) as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k)$$

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases}.$$  

The variance of $S$ can be obtained with $\text{Var}(S) = \left[ n(n-1)(2n+5) - \Sigma_t(t-1)(2t+5) \right]/18$, where $t$ is the extent of any given tie and $\Sigma_t$ denotes the summation over all ties. In the case that $n > 10$, the standard normal variable $z$ is computed with:

$$Z = \begin{cases} \frac{S - 1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S + 1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}.$$
In a two-sided trend test the $H_0$ should be rejected if $|z| \geq Z_{1-\alpha/2}$ at the $\alpha$ level of significance ($\alpha = 5\%$ in this study). A positive $Z$ indicates upward trend and vice versa (Kahya and Kalayci, 2004). The effect of the serial correlation on the MK test was eliminated using the Prewhitening technique (e.g. Yue and Wang, 2002).

3.2. Change point detection

Potential change points in the PI time series could be detected using Bayesian model (e.g. Xiong and Guo, 2004). The method which is often employed for homogeneity tests provides information about whether a distinct shift of the mean occurred in the time series. The PI series ($x_1, \ldots, x_n$) is divided into two segments by the change-point denoted as $k$ ($1 \leq k < n$). We analyzed the arithmetic mean of the PI series before and after the change point. The mean PI values of these two segments divided by the change point are denoted as $\mu_a$ and $\mu_b$. The prior distributions of both $\mu_a$ and $\mu_b$ are also assumed to be the normal distribution as:

$$x_i \sim N(\mu_a, \sigma^2) \ i = 1, 2, \ldots, k; \ and \ x_i \sim N(\mu_b, \sigma^2) \ i = k + 1, 2, \ldots, n$$

The $\sigma^2$ can be regarded as a constant and can be estimated by the PI series. The posterior distribution of the mean $\mu_a$ and $\mu_b$ can be determined based on the Bayesian theorem as:

$$\mu_a | X_k \sim N(\mu^*_a, \sigma^*_a)$$

Figure 4. Trends of (A) summer (JJA) precipitation, (B) the number of rainy days in summer, and (C) precipitation intensity within the Pearl River basin. The ◯ indicates no significant trend, ▲ indicates significant positive trend and ▼ indicates significant negative trend at the > 95% confidence level.

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DOI: 10.1002/asl
\[ \mu_a^* = \frac{n^* \mu_0 + \sum_{i=1}^{k} x_i}{n^* + k} \sigma_a^2 = \frac{\sigma^2}{n^* + k} \]

\[ \mu_b^* | X^{k+1} \sim N(\mu_b^*, \sigma_b^2) \]

\[ \mu_b^* = \frac{n^* \mu_0 + \sum_{i=1}^{n} x_i}{n^* + (n-k)} \sigma_b^2 \]

\[ \sigma_b^2 = \frac{n^* (n^* + (n-k))}{n^* + k} \]

The likelihood function based on Equation (4) can be formulated as:

\[ p(X|k, \mu_a, \mu_b) = \prod_{i=1}^{k} \frac{1}{\sqrt{2 \pi \sigma}} \exp \left[ -\frac{(x_i - \mu_a)^2}{2 \sigma^2} \right] \]

\[ \prod_{i=k+1}^{n} \frac{1}{\sqrt{2 \pi \sigma}} \exp \left[ -\frac{(x_i - \mu_b)^2}{2 \sigma^2} \right] \]

Based on the Bayesian theorem, the posterior distribution of the change-point \( k \) is derived as:

\[ p(k|X, \mu_a, \mu_b) = \frac{p(X|k, \mu_a, \mu_b) p(k)}{\sum_{j=1}^{n} p(X|j, \mu_a, \mu_b) p(j)} \]

Where \( p(j) \) represents the prior distribution of the change-point \( k \), and is often assumed to be a uniform distribution. The full conditional distribution of \( k \) can be estimated by Markov Chain Monte Carlo methods (e.g. Smith and Roberts, 1993). More detailed information can be taken from Xiong and Guo (2004). This method has been successfully used in change point detection within water level time series (Chen et al., 2008).

4. Results

4.1. Annual precipitation trends

Figure 2(A) shows that annual precipitation totals in the study region are not subject to significant trends with exception of two stations in the upper basin. However, precipitation patterns in the Pearl River basin are dominated by a significant negative trend in the number of rainy days (Figure 2(B)). No trends were observed for the number of rainy days at seven stations, accounting for 14.9% of the stations studied. It can be seen from Figure 2(C) that most stations of the Pearl River basin do not show any significant trends in terms of PI. Only 13 stations are characterized by significant positive trends, of which 6 stations are located in the Dongjiang and Beijiang basins and 7 stations distributed over the other basins. Figure 3 displays characteristics of annual extreme precipitation trends.

Figure 5. Extreme precipitation defined as precipitation exceeding mean \( \pm 0.25 \) std (A, B, C) and falling below mean \( \pm 0.25 \) std (D, E, F) in summer. A and D: total amount of the extreme precipitation in summer; B and E: number of days with precipitation exceeding/falling mean \( \pm \) std. C and F: precipitation intensity. The ◊ indicates significant no trend, ▲ indicates significant positive trend and ▼ indicates significant negative trend at the >95% confidence level.
No significant trends were identified regarding the APa totals (Figure 3(A)) and the related APa frequencies (Figure 3(B)). Significant positive APa trends can be detected at five stations and a significant negative APa trend at one station (Figure 3(C)). Most of the stations with positive trends are located in the southeastern region of the basin. More significant trends can be observed for the APb time series. Eight stations in the western Xijiang basin and six stations in the lower Dongjiang basin and the northern area are characterized by significant negative APb trends (Figure 3(D)). However, most stations of the Pearl River basin are dominated by nonsignificant trends regarding annual extreme precipitation (Figure 3(D)) and related frequency (Figure 3(E)). Figure 3(F) demonstrates that 20 stations in the Pearl River basin are dominated by a significantly decreasing APb intensity, accounting for 42.6% of the total stations studied. These 20 stations are widely distributed over the Pearl River basin showing no distinctive spatial patterns.

4.2. Summer precipitation trends
No significant trends were identified in the summer precipitation time series (Figure 4(A)). However, significant negative trends were detected in the number of rainy days during summer for majority of the stations in the Pearl River basin (Figure 4(B)). In particular, negative trends regarding the frequency of rainy days dominate in the Nanpanjiang, Beipanjiang, Hongshuihe, Xijiang and Qianjiang basins. No significant trends were found in the Youjiang, Zuojiang, and the upper Beijiang basins. The stations with significantly decreasing numbers of rainy days account for 55.3%
of the total stations studied. Figure 4(C) indicates that most stations do not show any significant trends regarding PI. Ten stations with significant positive PI trends are distributed over the Beipanjiang, Nanpanjiang, Beijiang and Dongjiang basins. The stations with significantly increasing summer PI account for 21.3% of the total stations studied. Figure 5 shows the changes regarding extreme precipitation events during summer. No significant trends were observed for the SPA totals (Figure 5(A)) and the related SPA frequencies (Figure 5(B)). Only a few stations (6) in the Nanpanjiang, Hongshuihe, and Youjiang basins are characterized positive SPA intensity trends (Figure 5(C)). Analogously, not many significant trends were found for the SPB totals (Figure 5(D)). Only six stations are featured by significant negative SPB trends. Significantly increasing SPB frequencies were identified in the Nanpanjiang and Beipanjiang basins (Figure 5(E)). Significantly decreasing SPB intensities were detected at nine stations which are distributed over the upper Xijiang, the lower Beijiang and the lower Dongjiang basins.

4.3. Winter precipitation trends

Only one station in the Pearl River basin shows a significant positive winter precipitation trend (Figure 6(A)). However, large parts of the upper Xijiang, Beijiang and Dongjiang basins are dominated by significant negative rainy day frequency trends (Figure 6(B)). Stations without significant rainy day frequency trends are mainly located in the central Pearl River basin. Figure 6(C) illustrates that significantly increasing winter precipitation intensities can only be observed for eight stations which are distributed dispersedly over the Xijiang River basin.

Figure 7 displays the stations with significant WPa (left panels) and WPb trends (right panels). Only few stations with significant winter trends were observed with regard to WPa values (Figure 7(A)), the respective number of rainy days (Figure 7(B)), or WPa intensity (Figure 7(C)). The stations with significant positive trends are mainly located in the Xijiang basin. No significant negative trends were detected across the Pearl River basin. Similarly, most stations in the Pearl River basin do not show any significant WPb trends (Figure 7(D)–(F)). Only one station in the upper Liujiang basin is characterized by a significant negative trend regarding the WPb rainfall days (Figure 7(E)). However, several significant negative trends regarding WPb totals and WPb intensity were identified for stations in the upper Xijiang, the lower Beijiang and the lower Dongjiang basins (Figure 7(D) and (F)).

4.4. Change point analysis

Figure 8 shows the spatial distribution of the change-point timing of the PI. As for the changes of the annual PI, the change points occurred mainly during the two time intervals i.e. early 1960s and 1980s. Abrupt changes in the Beipanjiang basin occurred during 1962–1963 (Figure 8(A)), in the upper Beijiang and Dongjiang basins around 1972, in the Nanpanjiang, lower Dongjiang and the lower Beijiang basins.
basins 1978–1982. In the Hongshuihe River, Youjiang River, Qianjiang River and Guijiang River, the abrupt changes occurred mainly during 1990–1994. It is evident that abrupt changes of the annual PI in the Nanpanjiang, Beipanjiang, Beijiang and Dongjiang basins occurred earlier than in the middle Pearl River basin (about 106°E–112°E) (Figure 8(A)). It can be seen from Figure 9(A) that annual PI of most stations increased after the change point, whereas stations in the upper Nanpanjiang basin are characterized by decreased PI after the change point.

Figure 8(B) illustrates that abrupt changes of PI in summer at most stations occurred in late 1970s, 1980s and early 1990s. Only two stations have abrupt changes in 1963. The changes in summer PI of most stations across the Pearl River basin occurred between 1973 and 1985. In the upper Beipanjiang, the lower Beijiang and the Dongjiang basins these events happened between 1963 and 1976 (Figure 8(B)). Again, the earlier timing of the summer PI changes in the Beipanjiang, the lower Beijiang, and the lower Dongjiang basins in comparison to the rest of the Pearl River basin (Figure 8(B)) is evident. Increased summer PI after the change point occurred for most of the stations in the Pearl River basin (Figure 10(B)). Particularly large increases of summer PI (>1.5 times the summer PI before the change point) can be identified for the stations in the Lijiang and Guijiang basins (Figure 9(B)). Figure 8(C) indicates that abrupt changes of PI at most stations were detected in late 1970s and early 1980s. The timing of abrupt changes happens somewhat earlier in the area of

![Figure 8](image-url)
the Dongjiang to the Nanpanjiang basins. The abrupt changes of winter PI in the upper Liujiang and Guijiang basins occurred between 1977 and 1979. Large winter PI increases as defined above occur more frequently when compared to that in terms of summer or annual changes of PI in the lower Beijiang, lower Dongjiang, Nanpanjiang, Beipanjiang, Zuojiang, Youjiang, Yujiang and upper Hongshuihe basins (Figure 9(C)). Figure 9(C) also displays that all of the stations in the Pearl River basin show increased PI after change points.

4.5. Asian monsoon intensity and moisture budget

Decreasing southwest and southeast monsoon intensities for the region can be observed in Figure 10. The inter-annual variability of the southwest monsoon intensity is relatively small (Figure 10(A)), whereas a larger inter-annual variability was detected in the southeast monsoon intensity. The change point analysis indicates that abrupt changes of the southeast monsoon intensity occurred roughly during 1972–1975. The concurrence of change points within the time series is an indicator towards the link between monsoon intensity variations and PI changes across the Pearl River basin. The decreased Asian monsoon intensity limits the northward extension of the summer monsoon to northern China. This atmospheric circulation pattern results in a stagnation of the rainfall belt over southern China and consequently increasing precipitation totals in that region (e.g. Yu et al., 2004; Wang and Zhou, 2005; Zhang et al., 2008a). Further
observatory evidences can be obtained from Figure 11 which presents moisture budget difference of different time intervals and the long term annual mean moisture amount (unit: kg \cdot m^{-1} \cdot s^{-1}). Figure 11 shows that, when compared to the long-term annual mean moisture, the moisture budget is increasing in the southern China over the time. In southern China, especially in the Pearl River basin, a moisture deficit is identified in 1956–1960 (Figure 11(A)). Figure 11(B) (1961–1975), shows that the area of the moisture deficit in southern China has decreased. Figure 11(C) (1976–1985) and Figure 11(D) (1986–2002) illustrate that the Pearl River basin is dominated by a moisture surplus. Both Figure 10 and Figure 11 provide a conclusive illustration of a weakened Asian monsoon system, which results in increased precipitation in the southern China including the Pearl River basin.

5. Summary and discussion

Trends and abrupt changes of the precipitation series in the Pearl River basin were systematically explored

Figure 10. Intensity of southwest monsoon (A) and southeast monsoon (B). The time intervals marked by gray regions denote the time when the abrupt changes occurred, i.e. 1972–1975. The black lines denote 12-month moving average.

using MK trend test and Bayesian model. Interesting conclusions are as follows:

Changes of the annual, summer and winter precipitation are not significant at >95% confidence level. However, significant decreasing trend can be identified in the number of rainy days. Similar results can also be achieved in the Yangtze River basin (Zhang et al., 2008a). They found increased numbers of no-rain days and increased PI values for the lower Yangtze River basin. Furthermore, the analyses revealed increased numbers of no-rain days and higher precipitation totals during certain time intervals which led to increased precipitation concentration (Zhang et al., 2008b). These observations were particularly valid for PI changes in winter. In winter, all the stations in the Pearl River basin show increased PI after the change point.

The changes of the extreme precipitation, defined as precipitation exceeding/falling mean ± std threshold, are systematically analyzed to explore the trends of extreme precipitation amount, frequency, and extreme PI. The results indicate most stations do not show any significant changes at the 95% confidence level regarding annual, summer or winter extreme precipitation. Some significant negative trends were detected in the total APb, SPb and the total WPb. Some significant negative trends were also found in PI of APb, SPb and WPb. However, some significant positive trends were observed in the total APa, SPa and the total WPa, and related precipitation frequency and PI.

The abrupt changes of the precipitation totals (annual, winter and summer precipitation totals) across the Pearl River basin occurred in late 1970s, 1980s and early 1990s. The comparison between mean PI before the change points and that after change points indicates that the PI generally increased after the change point. Abrupt changes leading to a weakening Asian monsoon occurred in 1972–1975. Analogously, the PI in the Pearl River basin increased after 1972–1975. This observation is underscoring the links between the variabilities of the Asian monsoon and precipitation intensities in the region. Our work in the Yangtze River basin (Zhang et al., 2008a) also corroborated the results of this study. Moisture flux analyses of this study showed an increased moisture flux in the recent decades. Particularly after 1975, the Pearl River basin is characterized by a positive moisture flux anomaly based on analyses of the moisture flux of time intervals of 1976–1985, 1986–2002 and the long-term average moisture flux of 1956–2002. Zhang et al. (2008a) also confirmed the influences of moisture budget, moisture flux on wet and dry status of the Yangtze River basin. Our results also show that the influences of monsoon activities on precipitation variations in the Pearl River basin are different from season to season. Obvious influences can be observed in winter rather than in summer. The summer conditions are strongly affected by convective and typhoon-induced precipitation patterns, which make the relations between monsoon activities and precipitation variations in the Pearl River basin more complicated.

The study pointed toward and partially explained some significant changes that occurred to precipitation patterns in the Pearl River basin. Besides, this study indicated increased precipitation variability and high-intensify precipitation events. However, low-intensity rainfall events have decreased. Besides, the precipitation amount has not changed too much, however, the precipitation variability increased within the time intervals divided by change points. These findings implied potentially increased risk for both agriculture and in locations subject to flooding, both urban and rural. Therefore, timely flood-control measures should be taken to enhance human mitigation to flood hazards under the changing climate across the Pearl River basin.

Acknowledgements

The work described in this paper was supported by a Direct Grant from the Faculty of Social Science, The Chinese University of Hong Kong (Project No. 4450183), a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CUHK405308), the Programme of Introducing Talents of Discipline to Universities – the 111 Project of Peking University (B080408), and by the National Basic Research Program (’973 Program’, Grant No. 2006CB405200). Cordial thanks should be extended to two anonymous reviewers and the associate editor, Dr. Roger Jones, for their invaluable comments and suggestions, which greatly improved the quality of this manuscript.

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