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Climatology and trends of wet spells in China

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With 7 Figures

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Summary

Climatological features and variations of wet spells, especially their trends over China, are investigated using a dataset of 594 meteorological stations across China from 1951 to 2003. The results show that the lower the latitude is, the longer the annual duration of wet spells is. The mean annual precipitation from wet spells is higher in southeastern coastal areas and much lower in western and northern China. The longest wet spells are found in Southwest China and the eastern Tibetan Plateau. The maximum daily precipitation of wet spells decreases from the southeast to the northwest, with the highest in southeastern coastal areas and the lowest in western China. The trends of wet spells exhibit striking regional differences. In most areas of western China, the annual number of days in wet spells has slightly increased, but significantly decreased over North China, Central China and Southwest China. The annual precipitation amount from wet spells displays significant downward trends in North China, eastern Northeast China and the eastern part of Southwest China, but upward trends in the eastern Tibetan Plateau and some southeastern coastal areas. Two clearly-contrasting regions in climatic changes of wet spells are the mid-lower reaches of the Yellow River and the eastern Tibetan Plateau, characterized by a decrease of about 24 days and an increase of about 6 days in annual wet spell days from 1953 to 2003, respectively.

1. Introduction

IPCC (2001) reported that overall global land precipitation has increased by about 2% since the beginning of the 20th century. In order to clarify whether frequency or intensity of climatic extremes have changed, Frich et al. (2001) studied various precipitation indices, including number of days with daily precipitation exceeding 10 mm and that of consecutive rainy days during the second half of the 20th century. Easterling et al. (2000) examined the trends in frequency and intensity of rainfall extremes in many parts of the world. Dai et al. (1998) discussed global variations in wet spells by calculating the Palmer drought severity index. All these studies showed that in many parts of the land areas over the world, the precipitation amount from wet spells and the number of heavy rainfall events have significantly increased. Regionally, Manton et al. (2001) investigated the trends of daily rainfall in Southeast Asia and reported that the number of rainy days has decreased significantly throughout Southeast Asia. Sun and Groisman (2000) found that precipitation extremes have increased even though the precipitation amount and frequency have declined in Siberia during the past 60 years. Tolika and Maheras (2005) studied the spatial and temporal characteristics of wet spells in Greece and divided wet spells into three classes (1–4, 5–10 and $\geq$11 days) in terms of their durations. In China, it has been documented that precipitation has significantly decreased in North China and increased in the reaches of the Yangtze River and in western China during the last several decades (Zhai et al., 1999, 2005; Wang et al., 2001). Over the regions with increasing trends in precipitation total, frequency of precipitation extremes has increased more significantly. However, the number of annual rainy days has dramatically decreased throughout most parts of China except for Northwest China (Zhai et al., 2005).

The hydrological cycle is supposed to be intensified under the global climate warming background (IPCC, 1996). One measure to assess such intensification is to examine whether the frequency of droughts and wet spells have increased. A lot of wet spells can result in extreme events, because those persistent rainfalls may lead to floods and other disasters. For instance, a wet spell lasted for half a month in eastern Northwest China and North China in autumn 2003. Numerous houses collapsed and many people became homeless. This study is intended to explore whether such a kind of event is becoming more extreme with stronger variability over China under the global warming background, through investigation of wet spells during the second half of the 20^{th} century.

In this paper we use daily precipitation data from about 600 meteorological stations in China in recent decades to examine climatological features of wet spells and their trends. The main objective is to better understand the changes of wet spells at regional scales. The data employed and analytical methods are described in Sect. 2. The climatology, extremes and trends in wet spells are discussed in Sects. 3, 4 and 5, respectively. The conclusions and discussions are given in Sect. 6.

2. Data and methods

2.1 Data

The employed daily precipitation dataset of 726 meteorological stations across China during the period of 1951–2003 was provided by National Meteorological Information Center, China Meteorological Administration. The quality of this dataset was first examined through quality-control

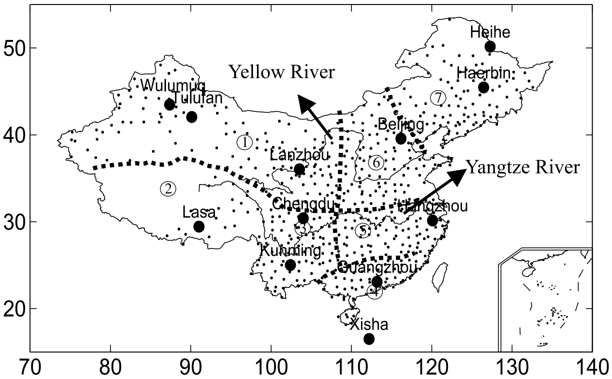

Fig. 1. Spatial distribution of the 594 meteorological stations (dots), 12 representative stations (large black dots) with their names, and the 7 climate divisions of China: ① Northwest ② the Tibetan Plateau ③ Southwest ④ South ⑤ Central ⑥ North ⑦ Northeast

procedures described by Feng et al. (2004). Less than 0.05% of the records were identified to be erroneous, suggesting that this dataset is of sufficient quality for analyzing and understanding the climate variability and changes in China. Additional efforts have been made by Zhai et al. (2005) to fill the missing data and correct the erroneous records. Therefore, these daily precipitation series are reliable for us to study wet spells. In this study, 594 stations are chosen from the aforementioned 726 stations. These selected stations, which were set up before 1953 and have not experienced large relocations since their establishments, cover all main climatological regions over China. The geographical distribution of these meteorological stations is displayed in Fig. 1.

2.2 Definition and analysis methods

In spring, a wet spell is a typical weather phenomenon in the southeastern coastal areas. In early summer from June till the first half of July, the wet spell noted as Meiyu always dominates the mid-lower reaches of the Yangtze River, with abundant rainfall and high humidity. During the period from mid-September to mid-October, the wet spell, which is named as West China Autumn Rainfall, occurs in Southwest China. Because of wide geographical area and complex climatology in China, the definitions of wet spells in previous studies vary from region to region as shown in Table 1. The definitions of wet spell are mostly

Table 1. Various definitions of wet spell in different regions over China

Name of regions	Number of rainy days	Total precipitation	Other criteria
Southwest China (Xu, 1991)	≥7 day	None	No dry days in the consecutive 7 rain days
Mid-lower reaches of the Yangtze River (Ouyang et al., 2000)	≥5 day	≥45 mm	Number of rain days more than 4
Northwest China (Lin and Zhang, 2003)	≥5 day	≥15 mm	Average cloud cover over 80%
South China (Xie, 2002)	≥5 day	≥10 mm	3 consecutive rainy days, and average cloud cover equal to 100%

based on the number of rainy days (with daily precipitation at least 0.10 mm). A minimum of 7 consecutive rainy days has been widely used as a criterion in Southwest China, but in other regions an event with only 5 rainy days is treated as a wet spell. In addition, precipitation amount during a wet spell is also taken into consideration. In the mid-lower reaches of the Yangtze River, for example, a wet spell is regarded as a period with precipitation amount more than 45 mm. In Northwest China, however, only 15 mm of rainfall is required in a wet spell. Moreover, cloud cover is also utilized in defining a wet spell in Northwest China and South China.

In order to explore the comparative characteristics of wet spells throughout China, a uniform standard for wet spells should be taken. Above all, a definition on rainy days should be declared. In this study, a rainy day refers to a day with precipitation accumulation greater than or equal to 0.10 mm, whereas a dry day represents a day without precipitation or with too little precipitation within 24 hours. Based on previous definitions used in different geographical locations of China, a comprehensive definition is generated with the following detailed criteria:

(1) In a wet spell, the number of rainy days should not be less than 4 days, and the first three days should not include a dry day.
(2) A wet spell is over whenever there are two consecutive dry days. The duration of a wet spell is defined as the number of days between the two consecutive dry days.

According to this definition, one dry day is allowed in a 5-day or 6-day wet spell, two discrete dry days in a 7-day or 8-day wet spell, and so on. Based on the above definition, the following indices on wet spell are calculated and studied:

(1) Annual number of days of wet spells.
(2) Annual precipitation amount during wet spells.
(3) Mean daily precipitation in a wet spell, calculated as the precipitation amount from a wet spell divided by the number of days of this wet spell.

In addition, some extreme indices of wet spells, such as the longest duration of wet spells and the highest daily precipitation amount of wet spells are also adopted to investigate the extreme events. In this paper, the extremes refer to the largest observation values during 1951–2003. All the aforementioned indices potentially reflect various attributes of wet spells.

Trends in wet spells are estimated using a Kendall's tau based slope estimator (Sen, 1968). This method is non-parametric and does not assume the distributional form for the data under investigation. Furthermore, it is not sensitive to outliers. Possible auto-correlation in the time series that may render the test of statistical significance of a trend unreliable is taken into account by using an iterative procedure introduced by Zhang et al. (2000) and refined by Wang and Swail (2001). Monte Carlo simulations indicate that this procedure is more appropriate for trend detections (Zhang and Zwiers, 2004). We use the procedure outlined in Wang et al. (2001).

3. Climatology of wet spells

Figure 2a shows the percentage of annual precipitation amount of wet spells relative to annual precipitation totals. Evidently, wet spell is a principle

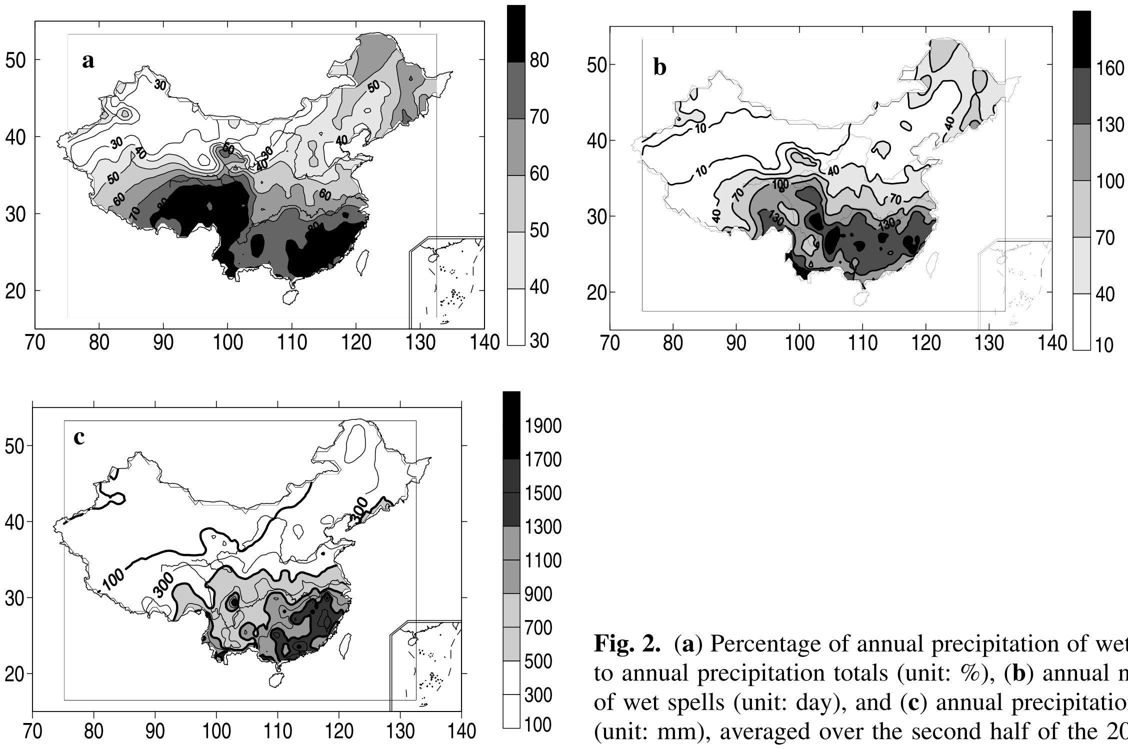

Fig. 2. (**a**) Percentage of annual precipitation of wet spells relative to annual precipitation totals (unit: %), (**b**) annual number of days of wet spells (unit: day), and (**c**) annual precipitation of wet spells (unit: mm), averaged over the second half of the 20th century

mode of annual precipitation that is highly geographically dependent. Generally, the index distribution is a strong function of latitudes: the lower the latitude is, the larger the percentage is. In southern China, rainfall from wet spells contributes more than half of the precipitation total, with a maximum of over 80% in the eastern Tibetan Plateau and southeastern coastal areas. In contrast, wet spells account for less than half in northern China, with a minimum of roughly 30% over arid and semi-arid Northwest China.

The annual number of days in wet spells (Fig. 2b) partly reflects the frequency of wet spell and is directly proportional to the duration of wet

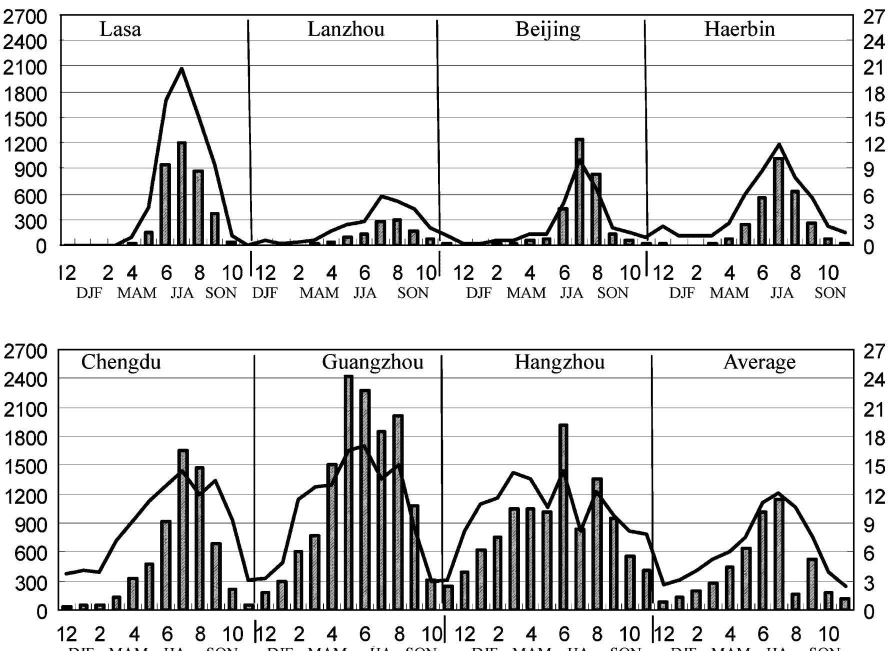

Fig. 3. The averaged monthly series of wet spells in 7 representative stations and in China. The bars indicate the monthly mean precipitation from wet spells (unit: mm, the left Y axis), and the curves are the monthly mean number of days in wet spells (unit: day, the right Y axis). (The numbers 12, 2, ... , 10 under the X axis stand for December, February, ... , October respectively. DJF, MAM, JJA and SON indicate winter, spring, summer and autumn of China respectively.)

spells. Its geographical distribution is characterized by high values in lower latitudes and significant small values in higher latitudes, similar to the percentage of precipitation from wet spells relative to annual precipitation totals (Fig. 2a). Wet spells frequently occur in the east side of the Tibetan Plateau and south to the Yangtze River, where the annual mean number of days in wet spells reaches as much as 100 days. In most parts of Northeast China, the annual number of days in wet spells is below 40 days. As expected, wet spells rarely occur over the arid and semi-arid areas of Northwest China, where the annual total number is below 10 days. For the most part, the distribution of wet spell days in Fig. 2b is broadly comparable to that of annual number of rainy days given by Sheng (1986).

The spatial distribution of precipitation amounts of wet spells (Fig. 2c) displays a gradual decrease from the southeast to the northwest. In southeastern coastal areas, the annual precipitation from wet spells is over 1300 mm. However, in Northwest China, especially in the arid area, the precipitation amount is less than 100 mm. In Northeast China and North China, there is about 200–300 mm precipitation from wet spells each year.

The monthly variations of wet spells at the seven representative stations in various climatic divisions (Fig. 3) indicate that wet spells mainly occur in warm seasons. In Haerbin and Beijing of the northern part of China, wet spells prevail only in summer. In Lanzhou of Northwest China, Chengdu of Southwest China and Lasa on the Tibetan Plateau, wet spells are concentrated in summer or early autumn. In Guangzhou and Hangzhou of the southern part of China, wet spells occur in spring and early autumn, as well as summer. In Hangzhou the number of days in wet spells and the corresponding precipitation are much larger in summer than in other seasons.

4. Extremes in wet spells

Particular attention should be paid to the extreme events of wet spells because of their tremendous impacts on the economy, society and environments (Karl et al., 1999). Extreme events in wet spells include long-time duration and heavy rainfall or snowfall. Figure 4 shows the spatial distributions of the indices for the two kinds of extreme events, namely the longest duration and maximum daily precipitation of wet spells during the past half century.

In Southwest China and the eastern Tibetan Plateau, the wet spell can persist for more than 60 days, even as long as 70 days in some areas of Southwest China. However, it is only about 20–30 days in North China and Northeast China and less than 20 days in most areas of Northwest China. On the whole, the extreme duration shares a similar pattern with the distribution of mean annual number of wet spell days (Fig. 2b).

The maximum mean daily precipitation of wet spells (Fig. 4b) decreases from the southeast to the northwest. In southeastern coastal areas, Central China and South China, the maximum daily precipitation reaches as much as 50 mm, whereas it is only approximately 30 mm in Northeast China and North China. The least maximum daily precipitation occurs in the areas west to 100° E and is less than 20 mm. All of the indices discussed so far consistently demonstrate that

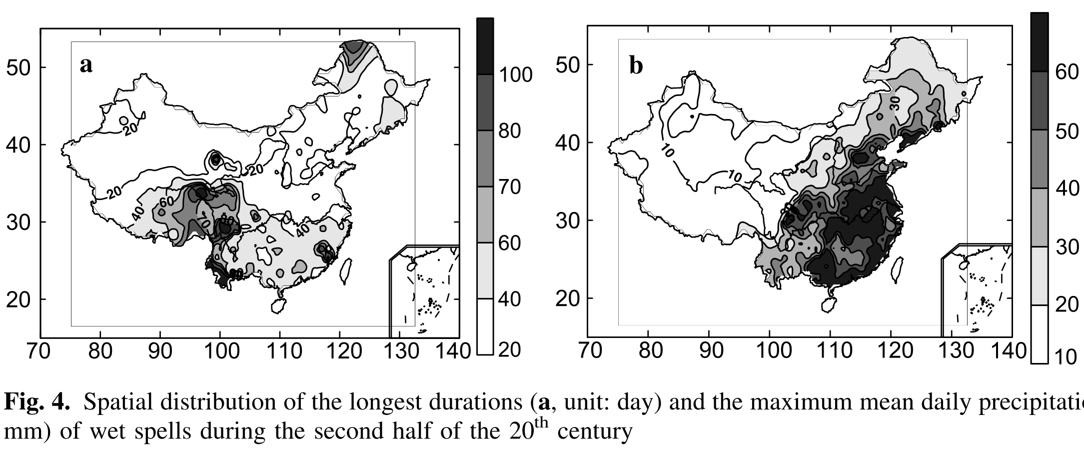

Fig. 4. Spatial distribution of the longest durations (**a**, unit: day) and the maximum mean daily precipitation amount (**b**, unit: mm) of wet spells during the second half of the 20th century

Table 2. Statistics of the extreme events in wet spells of 12 representative stations

Station name	Longest duration			Maximum intensity		
	Duration (d)	Onset date	Precipitation total (mm)	Daily precipitation (mm)	Onset date	Duration (d)
Heihe	23	8/15/1959	173.5	23.5	7/27/1963	9
Haerbin	27	7/5/1953	211.3	33.7	7/20/1952	7
Beijing	21	7/31/1957	176.2	59.5	8/3/1963	8
Hangzhou	39	2/4/1973	358.2	51.6	6/24/1999	8
Guangzhou	41	4/22/1960	223.9	65.1	4/28/1975	4
Xisha	27	11/29/1966	48.3	148.2	7/2/1961	5
Chengdu	51	7/24/1979	240.0	55.5	7/13/1973	6
Kunming	71	6/23/1958	515.4	48.0	8/9/1959	4
Lasa	56	7/13/1987	252.5	13.1	7/5/1960	5
Lanzhou	18	7/24/1976	111.0	23.1	8/11/1951	6
Wulumuqi	21	11/10/1966	13.4	22.9	6/9/1978	4
Tulufan	19	1/11/1954	5.3	2.0	9/24/1962	5

wet spells are relatively infrequent and weak in the western part of China.

In order to investigate detailed spatial and temporal features of extremes in wet spells, the durations, dates and precipitation totals of extreme events in 12 stations are summarized in Table 2. These selected stations, displayed in Fig. 1, are representative of different geographical and climatic divisions.

In the western part of Northwest China (e.g. Wulumuqi and Tulufan), the longest wet spells occur in the wintertime as the mode of consecutive snowfalls. In other stations of northern China (e.g. Haerbin and Beijing), the longest wet spells normally occur in the mid-summer. In southeastern coastal areas (e.g. Guangzhou and Hangzhou), they occur in the spring and can last for roughly 40 days.

The extreme daily precipitation in wet spells is stronger in the south than in the north. For example, a heaviest daily precipitation of 2.0 mm is observed in Tulufan of arid Northwest China, whereas extreme intensities of 148.2 mm and 65.1 mm are recorded in Xisha and Guangzhou of South China, respectively.

5. Trends in wet spells

Trends in wet spells represent the variations of wet spells associated with climate changes in the atmospheric circulation and are important indicators for droughts or floods. We analyzed the long-term tendency of annual number of days and total precipitation from wet spells based on slope estimator (Sen, 1968). The corresponding results are presented as follows.

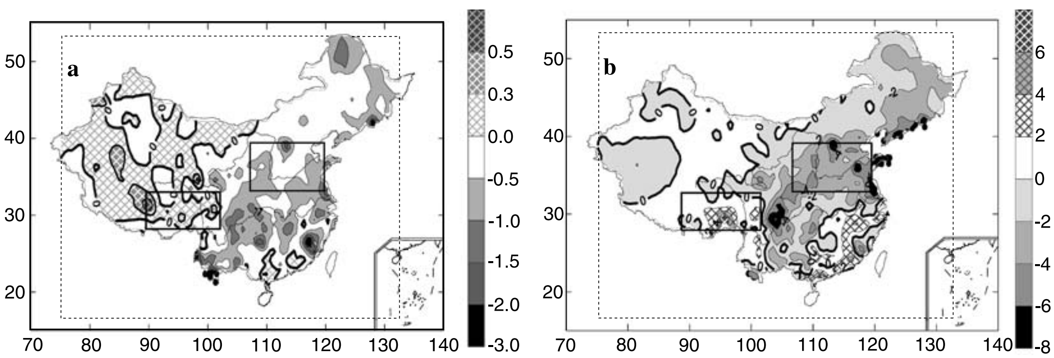

Fig. 5. Spatial distribution of trends in annual number of days (**a**, unit: day per yr) and annual precipitation of wet spells (**b**, unit: mm per yr). (The positive and negative values correspond to increasing and decreasing trends, respectively. The signs of ▲, ● indicate the stations with significant upward and downward trends at the 95% confidence level. Two key regions displayed in Figs. 6 and 7 are shown by rectangles)

5.1 Trends in annual number of days in wet spells

The spatial distribution of trends in annual number of days in wet spells is displayed in Fig. 5a. There is a clear distinction between western and eastern China, with a boundary approximately at the longitude 100° E. The wet spell days slightly increased in most areas of western China, but decreased over the eastern part of China, especially in Southwest China, North China and Central China, where a downward trend of about 5 days per decade is detected. Consistent with previous finding of the significant reduction in number of rainy days in most areas of China (Zhai et al., 2005), our examination confirms that wet spell days have decreased significantly in the eastern part of China. In Northwest China, the rainy days and the wet spell days have all increased slightly during the past 50 years. However in the western part of China (expect for Northwest China), the number of rainy days have decreased, although the number of days in wet spells increased.

5.2 Trends in precipitation totals of wet spells

As indicated in Fig. 5b, annual precipitation amount from wet spells shows significant negative trends of greater than 20 mm per decade in North China, the eastern part of Northeast China and Southwest China. In contrast, an increase of 20–40 mm per decade is noticeable in the eastern Tibetan Plateau, and also in some southeastern coastal areas. In most areas of the western part of China, neither evident increasing nor decreasing trends are detected.

Note that the geographical distribution of trends in annual precipitation from wet spells follows the patterns of annual number of days in wet spells (Fig. 5a) in North China, Southwest China and some western part of China. In the northern part of eastern China, the precipitation from wet spells displays a significant decrease like the precipitation totals (Zhai et al., 2005). However, the increase in the precipitation totals in the Yangtze River valley and most part of western China can not be explained in terms of the changes in the wet spell precipitation.

5.3. Comparison in regional patterns of wet spells

The preceding analysis reveals a decrease in wet spells in North China and Northeast China, and a moderate increase in the western part of China during the second half of the 20th century. As a result, the trends in the mid-lower reaches of the Yellow River (33–40° N, 106–117° E, marked in Fig. 5) are different from those of the eastern Tibetan Plateau (28–33° N, 90–102° E). In order to further examine the significant decreasing features in wet spells in North China during the second half of the 20th century, the eastern Tibetan Plateau is taken as a reference. Figures 6 and 7 compare the contrasting features of wet spells over these two important regions.

Firstly of all, annual number of days in wet spells (Fig. 6) has decreased by about 24 days in the half past century over the mid-lower reaches of the Yellow River, corresponding to a downward trend of 4.6 day per decade (significant). An

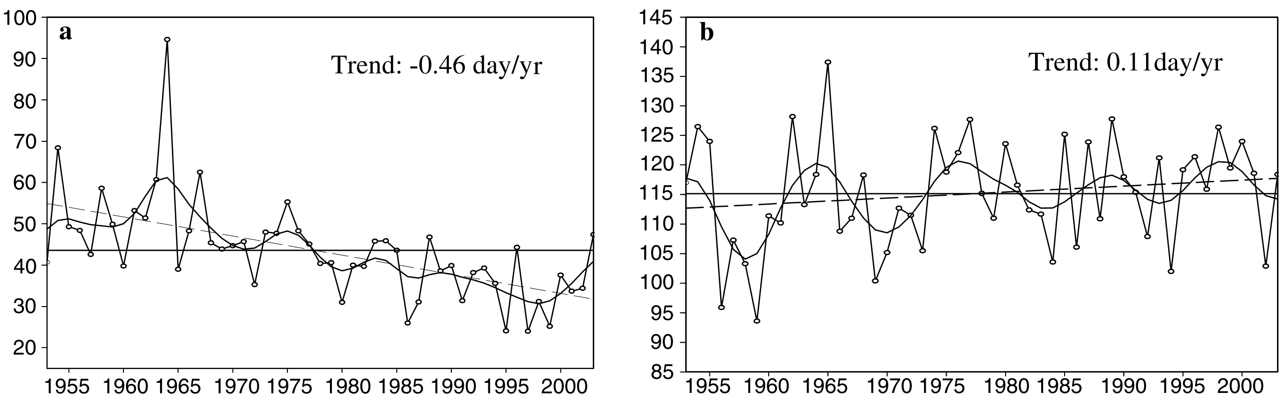

Fig. 6. Year-to-year variations of annual number of days in wet spells (dotted solid lines with dots, unit: day) in the mid-lower reaches of the Yellow River (**a**) and in the eastern Tibetan Plateau (**b**). (The solid curves and dashed lined indicate the 9-point Gaussian smoothes and linear trends respectively. The solid lines are the mean value during the past half century.)

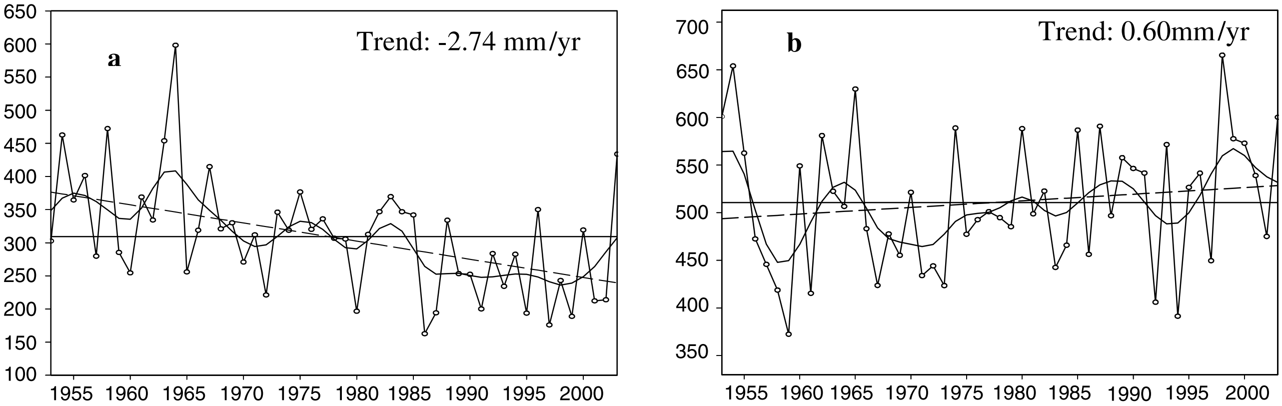

Fig. 7. Year-to-year variations of the annual precipitation amount in wet spells (dotted solid lines with dots, unit: mm) in the mid-lower reaches of the Yellow River (**a**) and in the eastern Tibetan Plateau (**b**). (The solid curves and dashed lined indicate the 9-point Gaussian smoothes and linear trends respectively. The solid lines are the mean value during the past half century.)

opposite tendency of much smaller magnitude is discernible over the eastern Tibetan Plateau; Annual wet spell days increased by about 6 days from 1953 to 2003, roughly 1.1 day per decade. Secondly, the mean annual precipitation amount from wet spells (Fig. 7) significantly decreased by 27.4 mm per decade over the mid-lower reaches of the Yellow River. In contrast, there is only an intensification of about 6.0 mm per decade over the eastern Tibetan Plateau. In summery, apparent differences between the two regions exist in trends of both the number of days and precipitation amount of wet spells.

6. Conclusions and discussions

This study investigates the climatological features and climatic trends of wet spells over China using the daily rainfall data of about 600 meteorological stations. The results are summarized as following:

(1) The wet spell is a principle mode of precipitation in China. By and large, the lower the latitude is, the longer the annual duration of wet spells is. The mean annual precipitation from wet spells is comparatively stronger in southeastern coastal areas and much weaker in the western and northern part of China.

(2) The longest wet spells are found in Southwest China and the eastern Tibetan Plateau and can persist for more than 60 days. In contrast, they last for less than 20–30 days in the northern part of China. The maximum mean daily precipitation from wet spells decreases from the southeast to the northwest, with the highest in southeastern coastal areas and the lowest value in the western part of China.

(3) The climatic trends in wet spells exhibit striking regional differences during the second half of the 20^{th} century. The number of days has slightly increased in most part of western China, but significantly decreased over the eastern part of China, especially in Southwest China, North China and Central China. Annual precipitation amount from wet spells shows a significant decreasing trend in North China, the eastern part of Northeast China and Southwest China, and displays an increasing trend in the eastern Tibetan Plateau and some southeastern coastal areas.

(4) Two distinct regions in changes of wet spells are the mid-lower reaches of the Yellow River and the eastern Tibetan Plateau, characteristic of a reduction of about 27.4 mm per decade and an enhancement of about 6.0 mm per decade during the past half century, respectively.

The spatial patterns of trends in annual number of days and precipitation amount from wet spells are largely comparable to those in annual number of rainy days and total amount (Zhai et al., 2005). This suggests that the changes in precipitation amount and frequency are closely associated with changes in wet spells. Although some studies showed that the precipitation amount from consecutive rainfall and the number of heavy rainfall events have significantly increased in many parts of the land area (Frich et al., 2001), this study reveals that the precipitation amount and the number of wet spell days have decreased markedly in the most eastern part of China. This inconsistency and the responsible mechanisms for the changes in wet spells can not be easily explained. Gong and Ho (2002) attributed the changes in rainfall in eastern China to the variations of sea surface temperatures in both the eastern tropical Pacific and the tropical Indian Ocean. However, Menon et al. (2002) and Ramanathan et al. (2001) suggested that the rainfall in monsoon system in the eastern part of China is substantially sensitive to the aerosol forcing. Yu et al. (2004) argured the mismatch of the stopped decline of monsoon in recent decades with the increase of pollutants and rejected the interpretation of the declined monsoon winds as a result of the increase in local aerosal-induced cooling. They even presented the observational evidences serving as a metric for validation of the climate model experiments that aim at explaining the causes of the precipitation trend pattern in eastern China. Other studies also suggested that changes in Asian ecosystems seem to be in association with monsoon climate over various time scales (Fu, 2003). More important, such kind of changes is also likely to be the regional impact of global warming. At the current stage, the physical feedbacks and mechanisms still remain ambiguous and vague (Zhao et al., 2005). Nevertheless, the physical process regulating the climatic variations of wet spells is an important issue and will be explored using reliable climate models in the future.

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