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ANALYSIS ON INTRA-ANNUAL INHOMOGENEITY OF RAINSTORM EVENTS IN GUANGXI

QIN Wei-jian (覃卫坚)[1, 2], LI Dong-liang (李栋梁)[1], LEI Xue-mei (雷雪梅)[3], QIN Zhi-nian (覃志年)[2]

(1. Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing 210044 China; 2. Guangxi Climate Center, Nanning 530022 China; 3. Guangxi Bureau of Meteorology, Nanning 530022 China)

Abstract: Based on the daily precipitation data of 83 stations in Guangxi and the NCEP/NCAR monthly reanalysis data from 1979 through 2008, the characteristics of spatial and temporal distribution and variation of the rainstorm concentration degree (RCD) and the rainstorm concentration period (RCP) are analyzed by using the methods of Monte Carlo test etc. The results are shown as follows. The rainstorm events are concentrated in April-September, taking up about 90% of the yearly rainfall total, and the percentages of rainstorms in the annual total precipitation have an increasing tendency. RCD in the east of Guangxi is larger than that in the west. The RCP in the northeast and southwest of Guangxi is later than that in the other regions, and has the earliest onset in the northern mountainous regions of Baise and southeast Guangxi. The RCD exhibits an increasing tendency in the northwest and the coastal region while showing a decreasing tendency in the other regions. On a long-term basis, the RCP in the east and coastal region has a postponing trend but tends to be earlier in the other regions. The proposed mechanism is as follows: If the geopotential height in the south of Qinghai-Tibet Plateau and the West Pacific has a highly negative anomaly in winter, the western Pacific subtropical high will be strong in summer, which increases the RCD in Guangxi. If the geopotential height has a highly positive anomaly in winter, the subtropical high will have a significant periodic oscillation in summer, which decreases the RCD in Guangxi. The value of RCD is high (low) in the area of northern mountainous regions of Guangxi and Beihai in strong (weak) South China Sea summer monsoon years, while in the other areas, the value of RCD is low (high).

Key words: rainstorm; rainstorm concentration degree (RCD); Monte Carlo test; Guangxi

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1 INTRODUCTION

Severe flood disasters often have quite a close relationship with the rainstorm concentration degree (RCD), i.e., the higher the RCP, the higher probability the flood disasters occur with. It is believed that the distribution pattern of extreme precipitation has changed because of the global warming[1, 2]. Thus, how should the distribution pattern of the extreme precipitation be analyzed? Some studies set a year as a circle in chronological order, considered the time of precipitation event as the vector, and used the precipitation as the model, and then obtained the inhomogeneity of the precipitation by using the calculation results from them.

The methods of selecting vectors in calculation are different, Zhang and Qian[3] used the pentad distribution, Yang et al.[4] used the monthly distribution, etc. For the model selection, Zhang et al.[5] used the pentad precipitation, Yang et al.[6] and Jian et al.[7] used extreme precipitation in a period, etc. The current study uses the daily rainstorm event as the model and the chronological order multiplied by 0.986° as the vector, and analyzes the distribution characteristics of intra-annual inhomogeneity of rainstorm events in Guangxi by using the calculation results from them.

Guangxi is located in low latitudes which is orographically high in the northwest and low in the southeast, with the southern border on the sea. The region often receives heavy rainfall and is influenced by such tropical synoptic systems as typhoons. There are normally serious economic losses and casualties which are related to heavy rain and flood every year. For example, in 1994, Guangxi suffered the worst

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Biography: QIN Wei-jian, Ph.D. candidate, senior engineer, primarily undertaking research on climate prediction and change.

Corresponding author: LI Dong-liang, e-mail: lidl@nuist.edu.cn

flood for the past 60 years, with the area over 1,650,000 hm^2 affected by the flood that caused losses worth of tens of billions yuan. The rainstorm in Guangxi has received much attention from researchers who have obtained many significant achievements. The causes of rainstorms in Guangxi have been studied by using the precipitation and NCEP/NCAR reanalysis data, and the results show that synoptic systems, including upper-level troughs, low vortexes, shear lines, fronts, typhoons, and southwest jets, influence the rainstorm in Guangxi[8]. Besides, research also illustrates that the interaction between the upper- and lower-level jets is one of the causes of rainstorms[9]. There is also a close relationship between the occurrence and break of regional rainstorms and the summer monsoon so that strong South China Sea (SCS) summer monsoon contributes to the water vapor transport to Guangxi[10]. Most of these studies focus on synoptic analysis and physical diagnosis, and all the findings show that the synoptic systems are the causes of rainstorms. Meanwhile some other studies have focused on the climatological perspective by using the precipitation data. Liao et al.[11] analyzed the distribution of rainstorms by using the wavelet method and the results showed that the rainstorm days have significant characteristics of periodic oscillations with strong 2-, 4-, 8-, 14-yearly periods, with the 2-yearly period being the strongest signal, and the rainstorm days in Guangxi exhibit a increasing tendency in recent years. Huang[12] and Li et al.[13] analyzed the spatial and temporal distribution of rainstorms and the results showed that the most rainstorm days are measured in the coastal region and the seasonal distribution exhibits a single-peak structure. In addition, Ou[14] studied the connection between the rainstorm days and the SCS summer monsoon onset time and the results show that an early (late) onset of the monsoon is linked with more (less) rainstorm days in the flood season in Guangxi. Although there are a lot of previous studies on the rainstorm in Guangxi, they mostly focused on the analysis of the atmospheric circulation, physical diagnosis, periodic oscillations, and spatial and temporal distribution characteristics of rainstorm days, which are not detailed enough, and few works focus on the concentration degree and period of heavy rainfall. So it is necessary to extract the peak period of maximum precipitation and analyze the climate tendencies and causes of the rainstorm concentration degree (RCD) and the rainstorm concentration period (RCP) in Guangxi, which are currently largely unexplored.

The study is conducted as follows. First, we analyze the seasonal variation and intra-annual structural distribution of rainstorms in Guangxi. Second, we study the climatic tendency of RCD and RCP which are tested by using the Monte Carlo technique. Third, we study the causes of intra-annual inhomogeneity of rainstorms. The study will contribute to efforts taken to mitigate floods and debris flows.

2 DATA AND METHODS

2.1 *Data*

For this study, we use the daily precipitation data in 1979−2008 from 83 stations in Guangxi. We also use the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) 850-hPa daily wind and humidity, and 500-hPa geopotential height reanalysis data during the 1948−2008 period. The rainstorm is defined as an event for which the 24-h precipitation reaches 50 mm in 20:00−20:00 the following day. A rainstorm station-event is defined as a station for which the 24-h precipitation reaches 50 mm in 20:00−20:00 the following day. The data of SCS summer monsoon intensity index are obtained from the National Climate Center's website.

2.2 *Definition of RCD and RCP*

The RCD and RCP are given by

$$RCD_i = \sqrt{R_{xi}^2 + R_{yi}^2} \Big/ R_i \tag{1}$$

$$RCP_i = \arctan(R_{xi} \big/ R_{yi}) \tag{2}$$

where RCD_i and RCP_i denote the RCD and RCP of the study period, respectively. *x and y* denote the two directions of decomposition of the vector which are mutually perpendicular[15]. Among them

$$R_{xi} = \sum_{j=1}^{N} r_{ij} * \sin\theta_j \tag{3}$$

$$R_{yi} = \sum_{j=1}^{N} r_{ij} * \cos\theta_j \tag{4}$$

where r_{ij}, R_i and θ_j denote the daily precipitation, total precipitation and corresponding azimuth for a given day (during 20:00−20:00), respectively, in which the daily precipitation is greater than 50 mm, with *i* for the year and *j* the chronological order in the study period.

2.3 *Climatic trend coefficient*

We analyze the climatic tendencies of rainstorms by utilizing the so-called climatic trend coefficient (r_{yt}). Since r_{yt} is a unitless quantity, its magnitude can be compared to other elements and utilized to estimate the intensity of secular trends for different physical elements. Besides, it is applicable, in particular, to the study on the long-term trends of geophysical elements and the spatial features of a large-scale geophysical field[16]. r_{yt} will be tested by the Monte Carlo technique and it is related to the regression coefficient b (climatic tendency rate or regression coefficient) through

$$r_{yt} = b(\sigma_t / \sigma_y) \quad (5)$$

where σ_t and σ_y denote the standard deviation of the time and analysis elements, respectively. b can be given in the form

$$y = a + bt \qquad (t = 1, 2, \cdots\cdots, n) \quad (6)$$

where a denotes a constant, y an analyzed element, and t the year.

2.4 *Monte Carlo test*

The Monte Carlo test is better than the t test in reflecting the actual correlation[17-19]. The threshold value of r_{yt} is shown in Table 1. If the absolute value of r_{yt}, the climate trend, is greater than the threshold value of the correlation coefficient for corresponding α =0.1, α =0.05, and α =0.01, the climate trend is considered to be slightly significant, moderately significant and highly significant, respectively.

Table 1. Threshold values of correlation coefficients.

α	0.1	0.05	0.01
Threshold values	0.296	0.350	0.450

3 SEASONAL DISTRIBUTION OF RAINSTORM IN GUANGXI

Figure 1 shows that the distribution of monthly rainstorm stations-events by using the daily precipitation data in 1979−2008. As shown in the figure, the monthly rainstorm states-events series distribute in a pattern of single peak, which increases gradually from January till its highest value in June with the amount of 111 stations-events, and then decreases gradually and reduces to the lowest in December (only 3 stations-events), with the annual rainstorm stations-events amounting to 467. Rainstorms mainly concentrate in the flood season (April−September), with the mean value being about 416 stations-events and taking up about 90% of the yearly total of rainstorm precipitation. There are 230 stations-events in the annually first flood season (April−June) of and 186 stations-events in the annually second flood season (July−September).

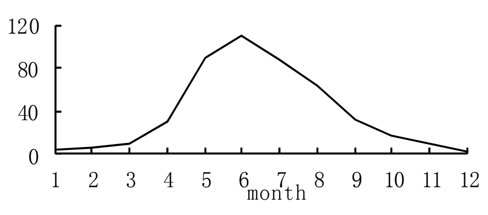

Figure 1. Monthly distribution of the rainstorm events in Guangxi (unit: stations-events).

4 STRUCTURAL DISTRIBUTION OF RAINSTORM DURING THE YEAR

The ratio of rainstorm rainfall to that of the annual total rainfall directly reflects the number and intensity of rainstorm processes. A higher proportion is associated with higher occurrence of extreme rainfall events with greater strength. Using the daily precipitation data in 1979−2008, Fig. 2a shows the distribution of the proportion of rainstorms amounting for the total annual precipitation. The results show that there are three large-value centers in Guangxi: one is the coastal region of Fangcheng and Dongxing, which has the maximum proportion and the annual rainstorm is more than half of the annual total precipitation. Another region is centered in Bama and Fengshan where the rainstorm takes up more than 30% of the total annual precipitation. The last large-value center is the northeastern mountainous part of Guangxi with two centers in Rong'an and Rongshui, respectively, where the proportion is approximately 30%. Affected by topography, the most extreme precipitation processes mostly occur in these three areas and the proportions in the other areas are between 18% and 30%.

Figure 2b shows the distribution of r_{yt}. As shown in the figure it tends to increase, which means that the possibility of extreme precipitation tends to increase. For Guanyang, Lingchuan, Xincheng, Yizhou, Longlin, Mashan, Wuming and Qinzhou, it increases significantly and passes the 95% confidence level in the Monte Carlo test. For Yongfu, Donglan, Pingguo, Zhongshan and Fangcheng, it increases significantly and passes the 90% confidence level. It is well known that the light, moderate and heavy rain may not cause a disaster but is beneficial to the growth of crops and the gain in water storage of reservoirs. The rainstorm proportions increase while the small rain, middle rain, large rain proportions reduce, which is not conducive to agricultural production and easy to cause droughts and floods. The r_{yt} increases significantly in the middle and northern areas of Guangxi, which are mountainous and hilly with favorable soil structure and landform, making it easy for debris flows to form there. It is clear that the increase of r_{yt} will cause the rise of the hazard of floods, landslides and debris flows.

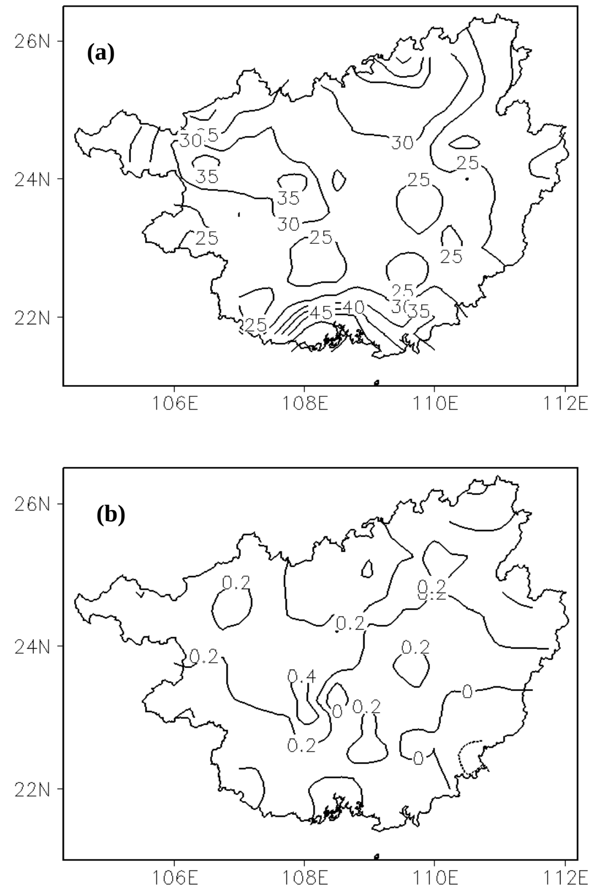

Figure 2. Spatial distribution of percentages (a, unit: %) of rainstorms accounting for the annual precipitation and their trends (b).

5 ANALYSIS OF RCD AND RCP IN GUANGXI

5.1 *Special distribution of RCD and RCP*

Figure 3a shows that the RCD distribution by using the daily precipitation data for 1979–2008. As indicated in the figure, the value of RCD in the east, more than 0.35, is higher than in the west, and the maximum RCD (0.48) appears in Xing'an and Rongxian. Therefore, the rainstorm events in the east are more concentrated and easier to trigger floods and debris flows, subjecting the area to high incidence of debris flows. The minimum RCD appears in the coastal area and the mountainous region of Baise (about 0.2), which suggests that rainstorms distribute more uniformly on the intra-annual scale. From the distribution of RCP (Fig. 3b), it is known that the RCP is the latest in the northeast and southwest of Guangxi, which is later than pentad 36 (early July), and the latest RCP occurs in Shangsi County, at about pentad 51 (mid-September); the RCP is the earliest in the northern mountainous region of Baise and southeast Guangxi, normally earlier than pentad 30 (late May), and the earliest RCP happens in Longlin County, at about pentad 17 (late March).

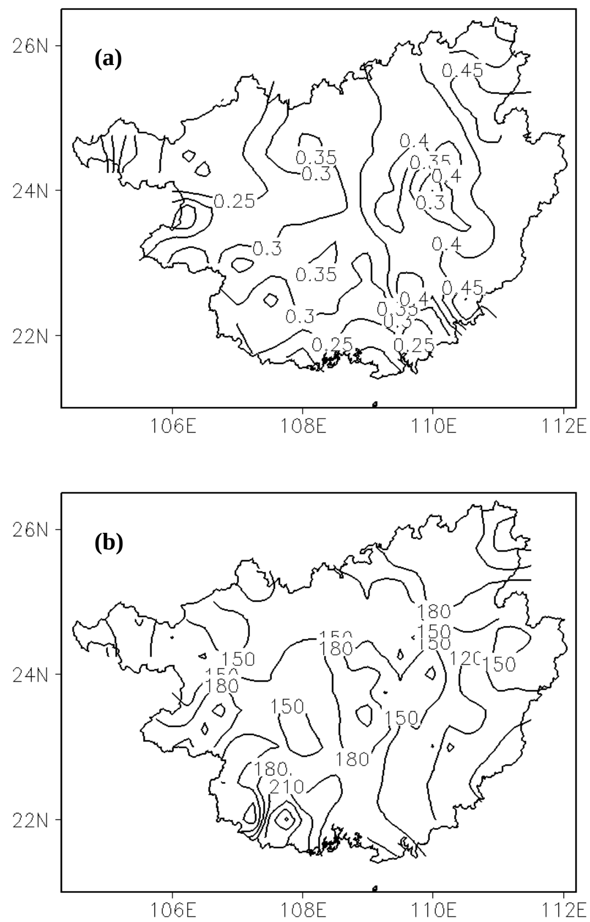

Figure 3. Spatial distribution of RCD (a) and RCP (b) in Guangxi.

5.2 *Analysis of the* r_{yt} *of RCD and RCP*

In the distribution of r_{yt} of RCD in the past 30 years (Fig. 4a), it is known that the r_{yt} of RCD exhibits an increasing tendency in the western and northern mountainous regions and coastal area. It tends to decrease in the middle and southeast of Guangxi. Its average value is −0.07 in Guangxi. It tends to increase most significantly in Rong'an (0.48) and passes the test of 95% confidence level. Secondly, the r_{yt} of RCD reaches 0.37 in Pingle, which passes the test of 95% confidence level and shows a significant increasing tendency. In Lingui it is 0.32 and has a significant trend. In Fengshan, Zhaoping and Hengxian, it has the most significant decreasing tendency, passes the test of 95% confidence level and decreases significantly. Then, the r_{yt} of RCD in Debao, Fuchuan, Xincheng, Xiangshan and Lingshan has a significant decreasing tendency and passes the test of 90% confidence level. Therefore, the northeastern mountainous region of Guangxi is the high prevalence area of debris flows where the RCD increases significantly. The occurrence possibilities of the debris flows have a significant increasing tendency. Rainstorm events in the middle and southeastern Guangxi have a scattering tendency.

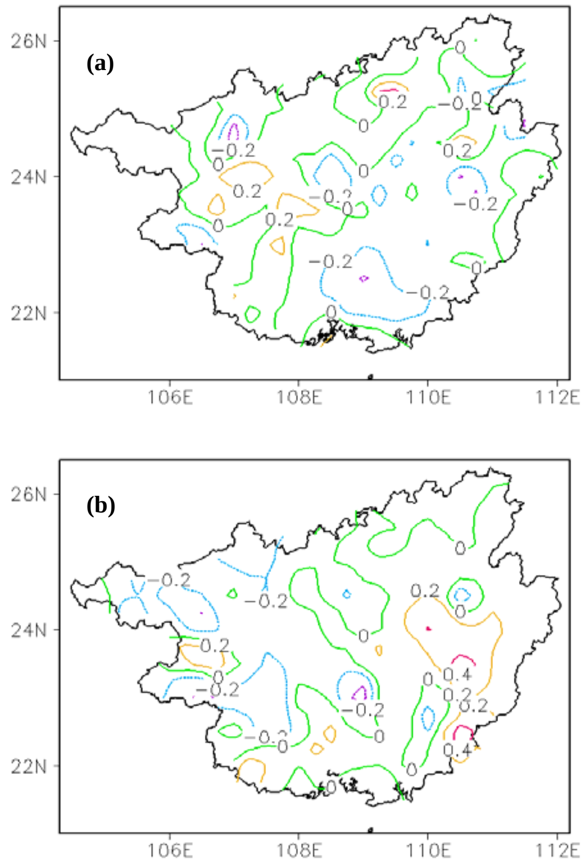

Figure 4. Spatial distribution of r_{yt} of RCD (a) and RCP (b).

As shown in Figure 4b, the r_{yt} of RCP shows a late tendency in the east of Guangxi and coastal regions but an early tendency in the middle and western regions. In the regions where it is positive, such as in Rongxian and Jinxiu Counties it is the largest (above 0.37), passes the test of 95% confidence level and tends to appear at later time. In Mengshan and Pingnan Counties it has a late tendency and passes the test of 90% confidence level. In the regions of negative tendency, such as Debao, Lingyun, Binyang, Longan, and Tiandeng, it has a significant tendency of getting ahead and passes the test of 90% confidence level. In Fusui and Tian'e Counties it passes the test of 90% confidence level and tends to appear at an earlier time.

6 ANALYSIS OF THE CAUSES OF DISTRIBUTION OF RCD IN GUANGXI

A rainstorm is the weather system on the meso- and micro-scale, but its intra-annual distribution is on the climate scale. Normally the rainstorm is caused by the interaction of weather systems with different temporal resolution, and the main rainstorm-influencing weather systems in Guangxi include jet streams, shear lines, frontal surfaces on the ground, tropical cyclones, southwest vortexes, upper-level troughs, subtropical convergence lines, etc., and they are closely related with the large-scale circulation systems, and are especially influenced by the monsoon significantly. Hereafter, we will explore the causes of inhomogeneous distribution of rainstorms associated with the atmospheric circulation and SCS summer monsoon in Guangxi.

6.1 *Analysis of atmospheric circulation*

Meso- and micro-scale weather systems can cause a short-term rainstorm process, but interaction between planetary, synoptic and meso- and micro-scale systems can make the rainstorm sustained over long durations. When the subtropical high is stretched towards the northeast of Guangxi, the maintenance of the subtropical high is the key element for the occurrence and development of the rainstorm in Guangxi. The subtropical high causes the rainstorm system to move quickly or slowly, stagnate or make loops, making the rainfall long and heavy in Guangxi. We make a composite of the 500-hPa height anomaly of the typical years (selected from the data of 1948−2008, the same below) and analyze the variation characteristics of the atmospheric circulation in order to explain the causes of rainstorm concentration.

The longitude-temporal cross-section along 30°N of the 500-hPa height anomaly of the typical strong years (1968, 1975, 1978, 2005, as shown in Fig. 5a), indicates a negative anomaly over the western Pacific and south of Tibetan Plateau in winter and spring, which is not conducive to water vapor transport and rainstorm occurrence, and decreases the rainstorm in winter and spring in Guangxi. In June−October, a positive anomaly occurs over the east and west of China along 30°N, which implies that the subtropical high in the western Pacific is strong and large and the ridge line is located westward, which exposes Guangxi to the western edge of the subtropical high and at the same time favors the transport of water vapor to Guangxi. Such situation of being higher in the east than in the west is beneficial to the development and maintenance of sustained rainstorm processes. On the other hand, the winter and spring usually witness negative anomaly over the southern Qinghai-Tibet Plateau and the western Pacific. It explains why rainstorms in Guangxi concentrate in summer and autumn and with a larger RCD.

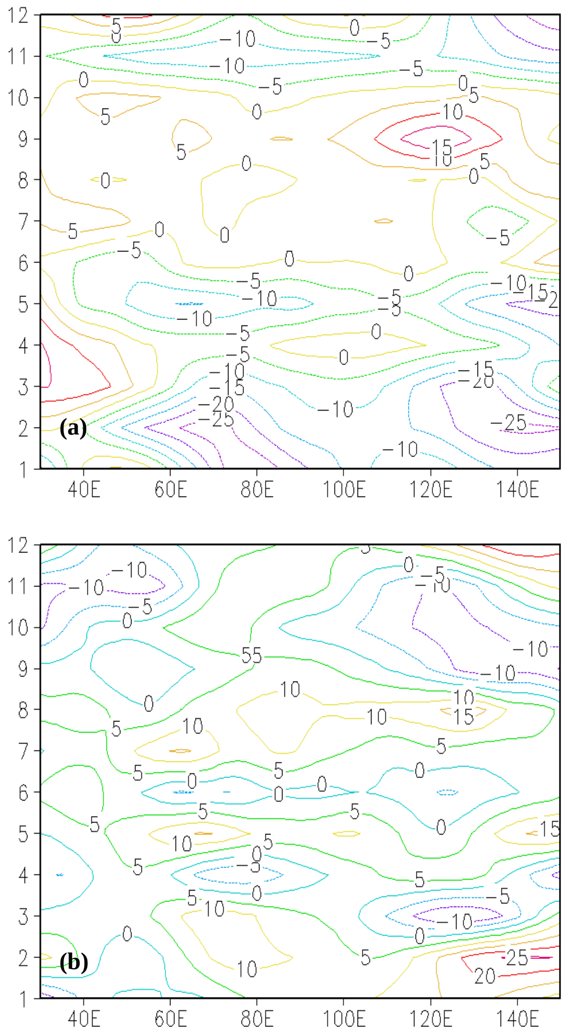

Figure 5. Composites of 500-hPa geopotential height anomaly (unit: gpm, a: large RCD years; b: small RCD years).

As shown in Fig. 5b, the composites of 500-hPa height anomaly in the typically weak years (1969, 1976, 1994, 2006) along 30°N differ much from those of the typically strong years. Positive anomalies occur over the southern Qinghai-Tibet Plateau and the western Pacific, being favorable for rainstorms to take place in the winter of Guangxi. There is a low-frequency oscillation with periods of 30 days over the southern Tibetan Plateau in spring and summer. The geopotential height field over the western Pacific also shows an obvious periodical change, with the anomalies being negative in March, June and September−November but positive in the other months. It indicates that the periodic variation of the atmospheric circulation results in the intra-annual homogeneous distribution of rainstorms in Guangxi, i.e., lessening the RCD.

6.2 *SCS summer monsoon*

The climatological changes in the precipitation and location of rain belts in China are closely associated with the Southeast Asian summer monsoon, and SCS is the area that sees the earliest onset of the East Asian summer monsoon, and the SCS summer monsoon onset marks the beginning of Southeast and East Asian summer monsoons and the arrival of the flood season[20-22]. Meanwhile, the SCS summer monsoon also affects the water vapor transport and the rain belt of a northward-going monsoon[23-26]. The strong and weak SCS summer monsoon years are selected for the past 30 years by using the data of an SCS summer monsoon intensity index obtained from National Climate Center's website. Then, the RCD anomaly of the strong years (Fig. 6a) and the weak years (Fig. 6b) are composed respectively. The results show that the RCD has a close relationship with the SCS summer monsoon such that in the mountainous region of northern Guangxi and Beihai the RCD is large in the strong years and small in the weak years. On the contrary, the RCD of the other regions is small (large) in the strong (weak) SCS summer monsoon years.

Water vapor transport plays an essential role in the sustained heavy rain process. To study the mechanism in which the SCS summer monsoon influences the RCD, we compose 850-hPa wind and water vapor fluxes in the flood season (from June to August) for the strong SCS summer monsoon years (1985, 2001, 2002) and the weak years (1988, 1995, 1998) respectively by using NCEP reanalysis data. As shown in Fig. 6c, there is an anticyclonic wind field in the ocean in the east off Taiwan Island in the strong years with an eastward location. A strong westerly wind is over India and the Bay of Bengal while a southerly wind is over Guangxi and low-level wind speed is relatively small. As shown in the composites of water vapor flux, strong water vapor is transported eastward from the India Ocean, crossing the bay and the Indochina Peninsula to go to the SCS, with a small northward component and thus little water vapor to Guangxi (Fig. 6c). It implies that a strong SCS summer monsoon is unfavorable to the water vapor transport to Guangxi from the bay to feed rainstorms in Guangxi, decreasing the RCD in most of Guangxi except Beihai and the northern mountainous regions. As shown in Fig. 6d, which is a composite of the 850-hPa wind and water vapor in the weak years, there is an anticyclone wind field over the sea east of Hainan Island and its center location is westward compared to that in the strong years. The southwest wind is strong over the bay and water vapor is intensely transported northeastward to Guangxi. A southwesterly wind is large over Guangxi. All of these are favorable to rainstorm occurrence in Guangxi. Therefore, the RCD is large in weak years in most regions of Guangxi except the northern mountainous region and Beihai.

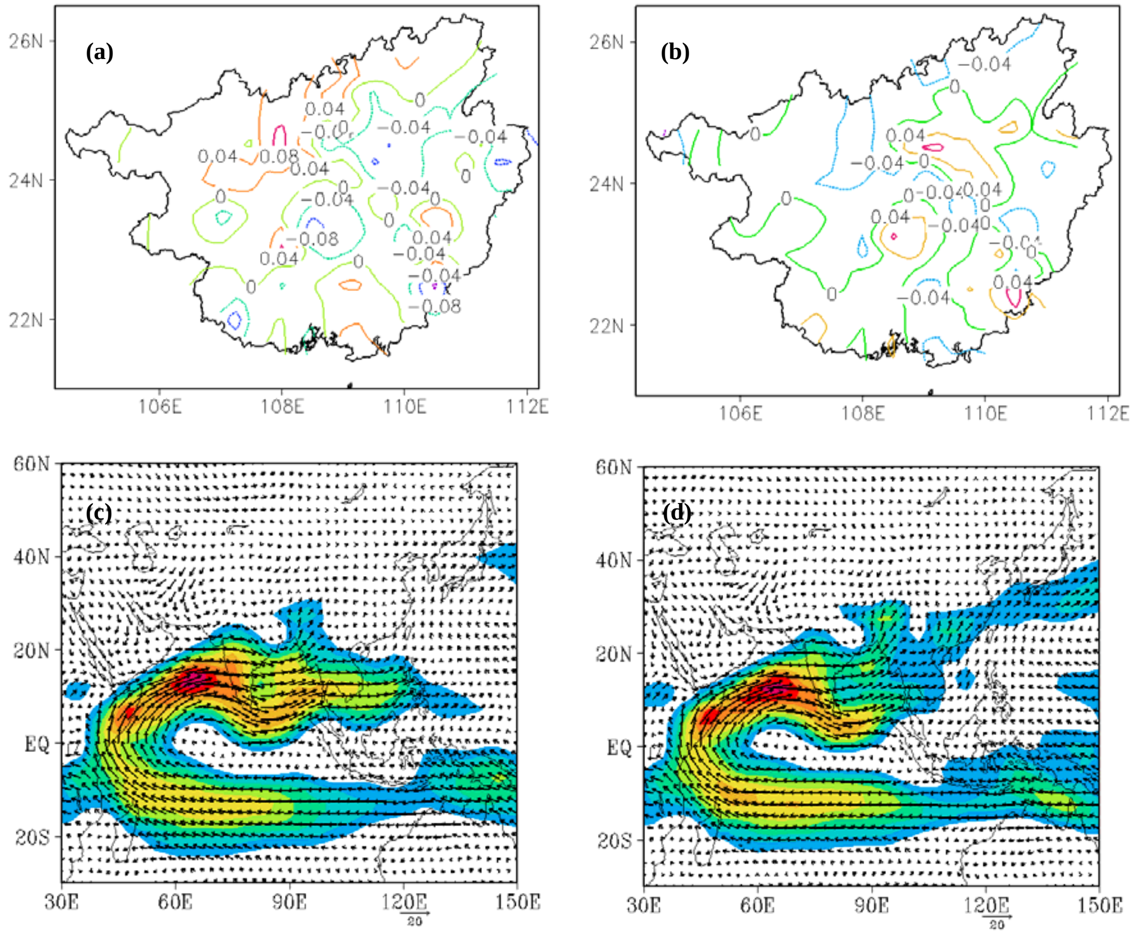

Figure 6. Distribution of the RCD anomalies in strong SCS summer monsoon years (a, c) and weak years (b, d) and 850-hPa stream field and water vapor flux (c, d; shaded regions indicate values larger than 30 $g \cdot s^{-1} \cdot hPa^{-1} \cdot cm^{-1}$).

7 SUMMARY AND DISCUSSION

In this article, we analyzed the seasonal variation and intra-annual structural distribution of rainstorms in Guangxi by using the precipitation data from ground meteorological stations and studied the spatial and temporal distribution characteristics of r_{yt} of RCD and RCP by using mathematical formulas. On the other hand, we also explored the causes of RCD distribution by using the NCEP/NCAR reanalysis data and composite method. From the discussion above, we can get the conclusions as follows:

(1) The rainstorm events are concentrated in April−September, taking up about 90% of the annual total rainfall, and most rainstorm events occur in June, with an average of 111 stations-events. The percentage of rainstorms accounting for the annual total precipitation has an increasing tendency, which means that the possibility of extreme precipitation tends to be increasing.

(2) The RCD in the east of Guangxi is larger than that in the west, with the RCD over 0.35. The RCD exhibits an increasing tendency in the northwest and coastal region of Guangxi while showing a decreasing tendency in the other regions. The RCP in the northeast and southwest of Guangxi appears later than in the other regions, with the northern mountainous region of Baise and southeast Guangxi being the earliest in appearance. On a long-term basis, the RCP in the east and coastal region has a postponing tendency and that in the other regions tends to take place at an earlier time.

(3) If the geopotential height in the south of Qinghai-Tibet Plateau and the West Pacific has a highly negative anomaly in winter and spring, the western Pacific subtropical high is strong and the ridge line is westward in summer, it will increase the RCD in Guangxi. If the geopotential height has a highly positive anomaly in winter and the subtropical high has a significant periodic oscillation in summer, it will decrease the RCD in Guangxi.

(4) The RCD has a close relationship with the SCS summer monsoon. Less (more) water vapor is transported to Guangxi and low-level wind speed is small (large) over the Bay of Bengal in strong (weak)

summer monsoon years. Therefore, the value of RCD is high (low) in the area of northern mountainous regions of Guangxi and Beihai in strong (weak) South China Sea summer monsoon years while being low (high) in the other areas.

In our analysis of the causes of RCD distribution of rainstorms influenced by the SCS summer monsoon, different features are shown between the northern mountainous regions of Guangxi and Beihai and the other regions. They may be due to the fact that rainstorms are greatly influenced by topography in the mountainous region and coastal Beihai is frequently affected by tropical cyclones. All of these characteristics and the causes of r_{yt} of RCD need to be studied further.

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