Article ID: 1006-8775(2013) 01-0097-07

STUDY OF RELATIONSHIP BETWEEN URBANIZATION SPEED AND CHANGE IN SPATIAL DISTRIBUTION OF RAINFALL OVER SHANGHAI

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Abstract: Using daily rainfall data of 11 observatory stations over Shanghai for the period 1960–2007, the spatial differences of rainfall over the Shanghai region during periods with slow and rapid urbanization respectively are investigated based on spatial standard deviation of rainfall and its relative variables. Results show that spatial differences increase with the acceleration of urbanization. Spatial distributions of annual rainfall and rainstorm frequency exhibit distinct urban ‘rain-island’ features during the rapid period of urbanization (1960-1983) while it is opposite in the case of slow urbanization (1984-2007). Changes in the spatial distribution of annual rainfall trends also take place during different periods. Specifically, the variation of annual rainfall exhibits consistent trends over the Shanghai region in the slow urbanization periods. However, inconsistent spatial distribution of variations has taken place over the central districts and suburbs of Shanghai during the rapid urbanization stage. Since the speeding-up of urbanization, the annual rainfall amount over central districts of Shanghai tends to increase while that in the suburbs shows a decreasing trend. In addition, as far as different seasons are concerned, the speed of urbanization exerts insignificant influences on the spatial distribution of rainfall during winter and spring. On the contrary, the rainfall during summer and autumn (especially summer) is featured with an island effect during the rapid urbanization period.

Key words: urbanization; spatial normalization; rainfall; spatial distribution; Shanghai

CLC number: X16 **Document code:** A

1 INTRODUCTION

Recent climate change, marked by global warming, is likely to influence the distributions of water resources[1-5]. Deng et al.[6] and Ren et al.[7] indicated that the present climate change is in close association with human activities. With the increasing frequency of human activities, changes in underlying surface situation brought by landuse have become increasingly distinct[8], which exerts great impacts on variations of climate elements by influencing movements of atmospheric heat and water vapor[8-10]. Therefore, for major metropolises like Shanghai, changes in its underlying surface condition brought by urban development may influence the spatial distribution of climate elements including temperature[11], precipitation, etc.

Studies of Zhou and Yang[12], Zhou et al.[13] and Yu et al.[14] on precipitation differences between downtown and rural areas in Shanghai, Nanjing and Tianjin showed that rainfall distributions in large cities exhibit features of urban rainfall islands while the summer rainfall distribution in Beijing[15] and annual rainfall distribution in Chengdu[16] reflect distinct features of urban drought islands. Further researches of Sun and Shu[17] and Wang et al.[18, 19] on the change of seasonal rainfall distribution in Beijing indicate that urban influences on rainfall distribution differ with seasons.

What are the relationships between the urbanization progress and change of precipitation distribution for Shanghai, which is among the fastest urbanized cities in China? The answer to this question may clarify the influences of urbanization on climatological change of precipitation, as well as the present state and variation trend of water resources in Shanghai. In this paper, based on the analysis on the spatial inhomogeneity of annual precipitation change in Shanghai, characteristics of precipitation distribution under different urbanization stages are

Received 2011-10-20; **Revised** 2012-12-10; **Accepted** 2013-01-15

Foundation item: Pilot Special Project of Chinese Academy of Sciences (XDA05090204); Public Welfare Meteorological Program (GYHY201006020); National Natural Science Foundation (41075068).

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discussed. Moreover, various spatial distributions of annual rainfall trend and seasonal precipitation are further investigated to understand detailed urbanization influences in Shanghai.

2 DATA AND METHODS

Datasets used in this paper include: (1) daily rainfall data of 11 observatory stations over Shanghai for the period of 1960–2007 from Shanghai Meteorological Bureau; (2) annual data of building area, cultivation area, population density, energy consumption during 1961–2007 from *Shanghai Statistics Yearbook*.

Spatial standard deviation of rainfall is used to investigate spatial differences of rainfall over the Shanghai region during periods of slow and rapid urbanization, respectively. Here, the standard deviation of rainfall is computed with the following equation[19].

$$R_{ni} = (p_{ni} - p_n) / \sigma^p{}_n ,$$

(n=1960, 1961, ⋯⋯, 2007; i=1,⋯⋯, 11)

where n and i denote the number of years and observation stations respectively, R_{ni} and p_{ni} are the relative and observed precipitation of station i in year n respectively, p_n and $\sigma^p{}_n$ the average precipitation and rainfall standard deviation of multi-stations in year n respectively.

3 DEFINITION OF SLOW AND RAPID ACCELERATION

As is well known, rapid urbanization is accompanied by fast increases of related factors including population density, area of built roads, and energy consumption. Therefore, the factors described above are used to define different urbanization stages in this paper. As is shown in Figure 1, the building area, population density and industrial energy consumption have increased rapidly since mid-1980s, while the opposite is the case for the cultivation area. Significance tests of the difference between the means of urbanization factors before and after the mid-1980s indicated that the differences between the two stages are significant at the 0.01 level. Moreover, the variation trends of constructed road area, population density, industrial energy consumption and cultivation after the mid-1980s are 122, 5, 2.3 and 10 times larger than those before it, respectively. Both the changes of total amount and variation velocities of these factors suggest that the progress of urbanization after the mid-1980s has increased more rapidly compared with that before it. Therefore, the period from 1960 to 2007 was divided into two sections, one from 1960 to 1983 and the other from 1984 to 2007, which were then defined as the slow and rapid urbanization respectively.

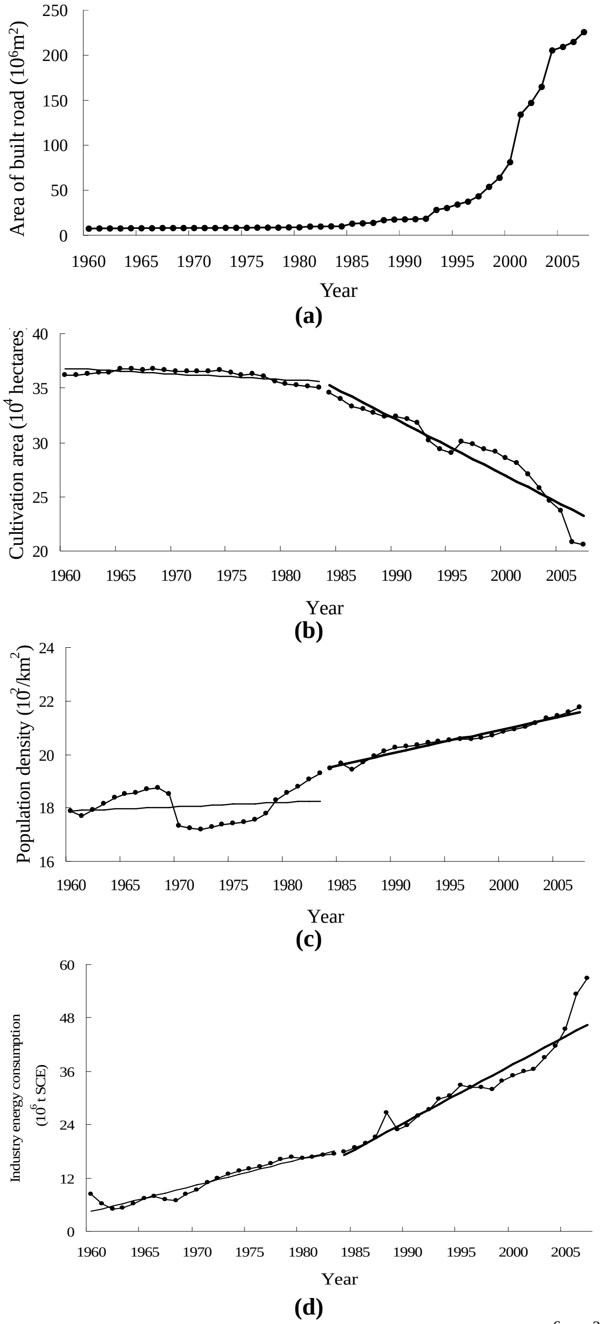


Figure 1. Area of constructed roads (a, unit: 10^6 m^2), cultivation area (b, unit: 10^4 hectares), human density (c, unit: $10^2/km^2$) and industrial energy consumption (d, unit: tons of standard coal) (thin and thick slant lines representing trends during 1960-1983 and 1984-2007 respectively).

4 SPATIAL DIFFERENCES OF ANNUAL PRECIPITATION IN SHANGHAI DURING DIFFERENT STAGES OF UNBANIZATION

It can be seen from the spatial standard deviation of annual precipitation over the 11 observational stations in Shanghai (Figure 2a) that the average standard deviation (93.0 mm) during the rapid urbanization stage is evidently larger than that during the slow stage (81.2 mm). The increasing trend (1.4 mm/yr, significant at the 0.10 level) of annual precipitation standard deviation during the rapid urbanization stage is 2.5 times larger than that of the slow increasing trend (0.4 mm/yr, insignificant). Spatial inhomogeneity and variation of annual precipitation reflected by spatial standard deviation have increased with the enlargement of urban-suburban differences brought about by the accelerating process of urbanization. Such features can be clearly seen from the comparison between Xujiahui (an urban station) and Minhang (a suburban station) in Figure 2b. Therefore, changes in the spatial distribution of precipitation in Shanghai may be influenced by changes of urbanization speed.

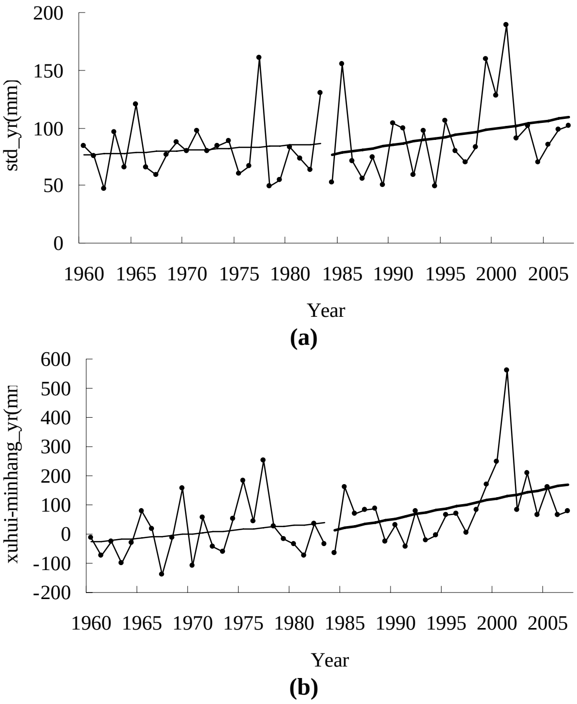


Figure 2. Distribution of annual variation of spatially standardized annual rainfall in Shanghai (a) and Xuhui minus Minhang (b) (unit: mm; thin and thick slant lines representing trends during 1960-1983 and 1984-2007 respectively).

Figure 3 shows the spatial distribution of standardized relative precipitation in Shanghai during 1960–1983 (the slow urbanization stage) and 1984–2007 (the rapid urbanization stage). It can be seen that the distribution of annual precipitation is spatially homogenous in Shanghai during the slow urbanization stage (Figure 3a), in which the symbol and range of relative precipitation for 70% of the observation stations are consistent. Moreover, the differences between central districts, represented by Xujiahui, and the suburbs, represented by Minhang, are not remarkable. For the rapid urbanization (Figure 3b), however, the decreasing of same-symbol percentage of relative precipitation suggests that the spatial distribution of precipitation becomes more inhomogeneous. The annual rainfall over central districts, including Xujiahui and Pudong, are much more than that for other stations. It can be concluded that with the rapid urbanization the annual precipitation over the central districts are much more than that over the suburbs.

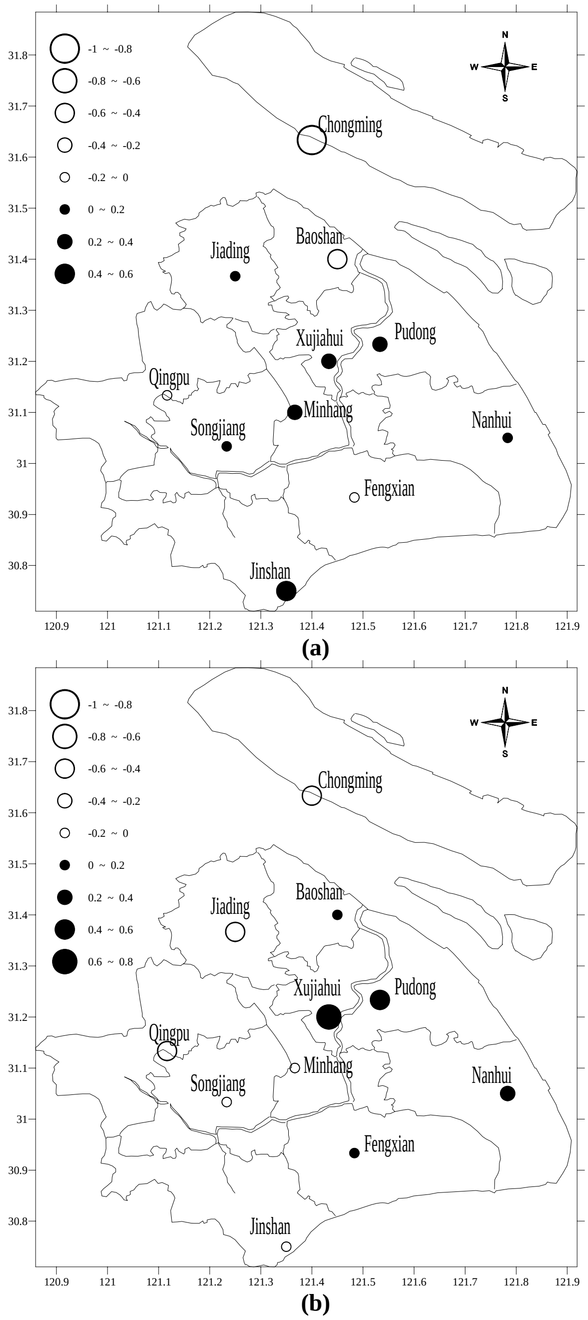
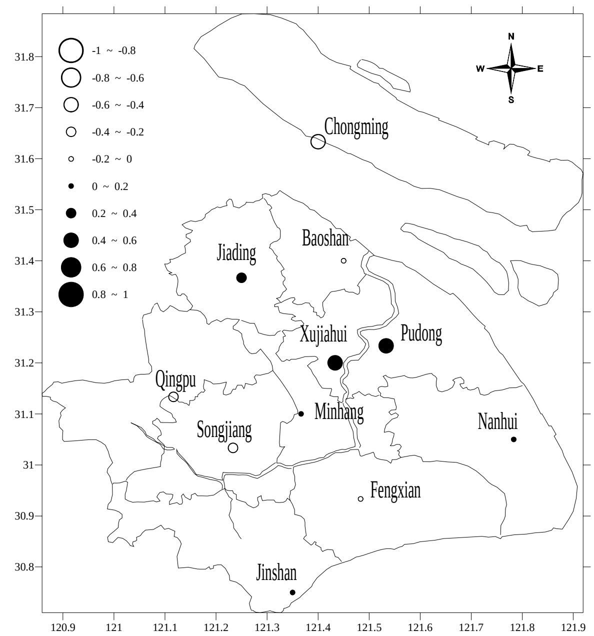


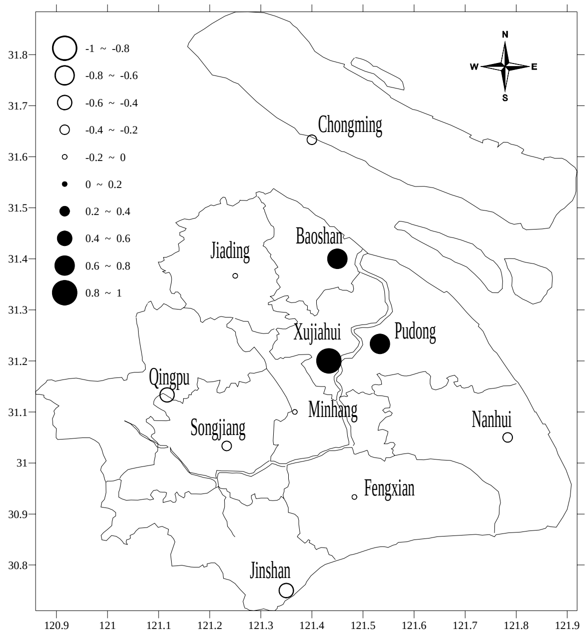
Figure 3. Distribution of standardized relative annual rainfall (a: 1960-1983; b: 1984-2007; solid/hollow circles denoting above/below normal rainfall; extent of above or below normal amount proportional to circle diameter).

As is shown in the above analysis, great changes have taken place in the pattern of annual rainfall distribution since the rapid urbanization. Precipitation generally maximized in districts such as Xujiahui and Pudong in years (figure omitted) with rainfall being no more than normal during the rapid urbanization. Therefore, the urban rainfall island effect mainly appears in this stage and is similar in cases with rainfall above and below normal.

From the distribution pattern of spatially standardized annual rainfall strength (defined by annual rainfall minus the number of days of rainfall above 0.1 mm) during different urbanization stages (Figure 4), it can be seen that the annual rainfall strength over the central districts is much larger than that over the suburbs during the rapid urbanization. For example, standardized relative rainfall reaches 0.99 and 0.644 at the Xujiahui and Pudong stations respectively. However, the relative strength of rainfall at Jiading, Minhang, Nanhui and Jinshan has converted from positive during the slow urbanization to negative during the rapid urbanization. It means that the rainfall strength also centers more on the central districts in the rapid stage.



(a)



(b)

Figure 4. Same as Figure 3 but for the strength of standardized relative annual rainfall in Shanghai.

Spatial distributions of rainfall (including rainstorm) days during the two stages (figures omitted) are also investigated in this paper. It shows that the acceleration of urbanization also exerts similar influences on rain days with rainfall stronger than rainstorm, in addition to rain days with daily rainfall less than 50 mm. It should be noted that apart from the central districts represented by Xujiahui, Pudong is also included in a large-value center due to its process of urbanization. In other words, corresponding to the enlargement of urban area, the coverage of rainfall has expanded in the rapid stage of urbanization.

5 SPATIAL DIFFERENCES FOR VARIATION TREND OF ANNUAL PRECIPITATION IN SHANGHAI DURING DIFFERENT STAGES OF URBANIZATION

To further investigate the differences in spatial distribution of rainfall variation during different stages of urbanization, Figure 5 shows linear trends of annual precipitation in Shanghai during 1960–1983 and 1984–2007. The annual precipitation exhibits consistent increasing trends in spite of different values from the 1960s to the 1980s. The annual rainfall shows increasing and decreasing trends over the central districts (i.e. Xujiahui and Pudong) and the suburbs respectively during the 1980s to 2000s. It indicates that the variation trend of annual rainfall reflects distinct characteristics of inhomogeneous spatial distribution due to different speed of urbanization over these areas.

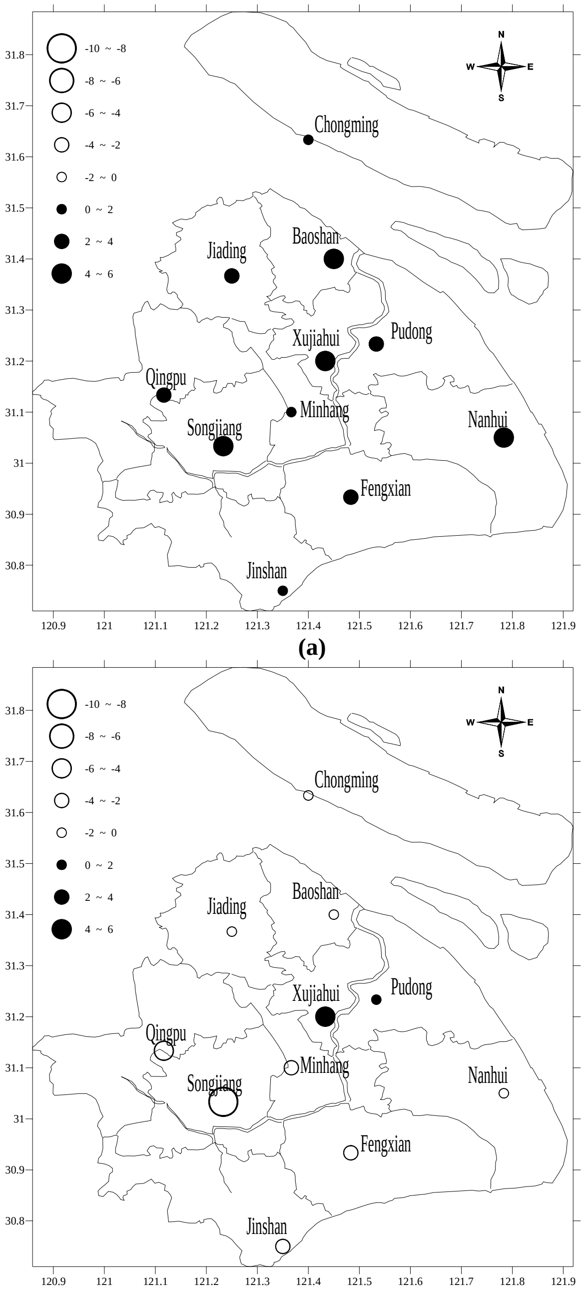
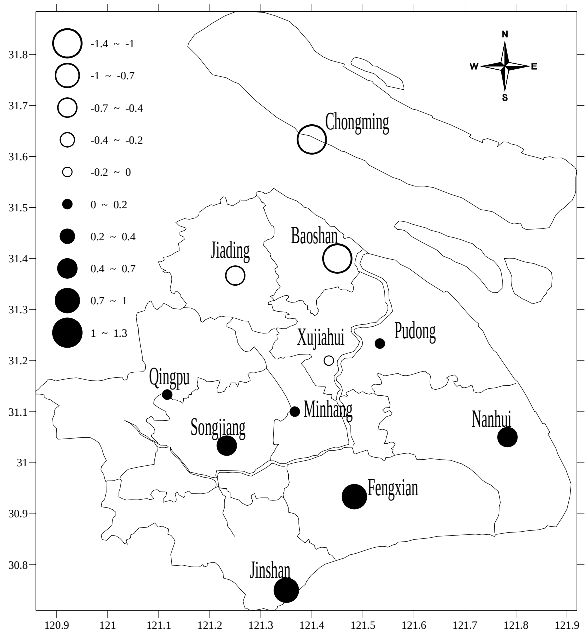


Figure 5. Linear trend of annual rainfall in Shanghai during 1960-1983 (a) and 1984-2007 (b) (unit: mm/yr).

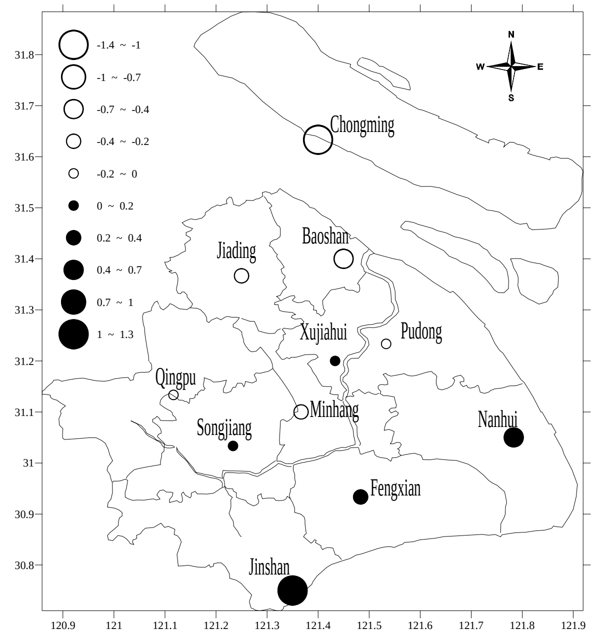
6 SPATIAL DIFFERENCES OF SEASONAL RAINFALL IN SHANGHAI DURING DIFFERENT STAGES OF URBANIZATION

Annual rainfall is accumulated by different seasonal rainfall. Are influences of urbanization on spatial rainfall distribution consistent in different seasons? We will further discuss this issue in the next paper. Comparisons of spatial distributions of relative rainfall in the four seasons during the slow and rapid urbanization show that spatial distributions of seasonal rainfall in both winter and spring exhibit a pattern of being “more in the south and less in the north” in whichever urbanization stage. In winter (Figures 6a and 6b), the seasonal rainfall at Xujiahui has changed from being relatively small in the slow stage to relatively large in the rapid stage. The case is opposite for Pudong, however, another observation station in a central district. The change in rainfall distribution in spring (figure omitted) is similar to that in winter. Therefore, urbanization exerts unclear impacts on spatial differences of both winter and spring rainfall in Shanghai.

Different from the features of winter and spring rainfall analyzed above, spatial differences of summer and autumn rainfall (Figures 6c and 6d) reflect remarkable urban rainfall island features (i.e. more rainfall for central districts) during the rapid urbanization, especially in summer. In the slow urbanization, summer rainfall at the suburban Jiading station (with relative rainfall at 0.567) is the most by comparing with other stations, while rainfall at the central-district Xujiahui station (with relative rainfall at 0.444) is less than that of Jiading. The spatial coverage of summer rainfall substantially increases during the rapid urbanization. Relatively more rainfall concentrates at only 3/10 of the stations, in which rainfall at central-district stations, including Xujiahui and Pudong, with relative rainfall at 0.685 and 0.445 respectively, are the most relative to other stations. This is in agreement with the feature of urban rainfall island brought about by the faster pace of urbanization over the central districts relative to the suburbs. Spatial differences in autumn rainfall between the two stages also reflect, to some extent, the feature of urban rainfall island induced by the faster urbanization progress.



(a)



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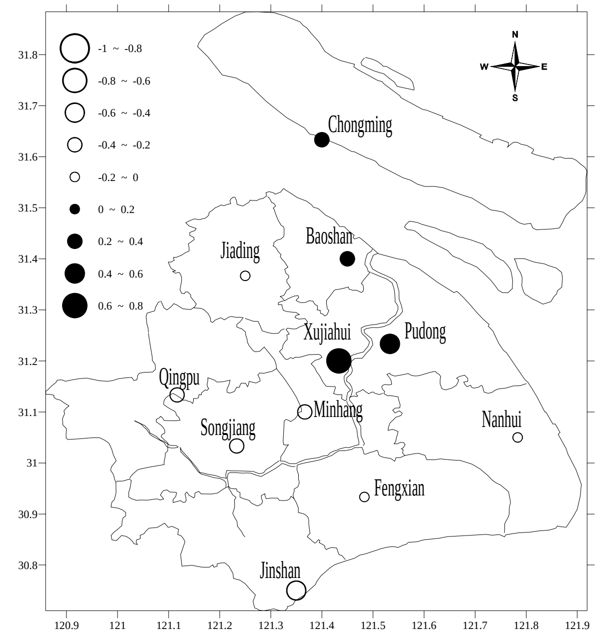
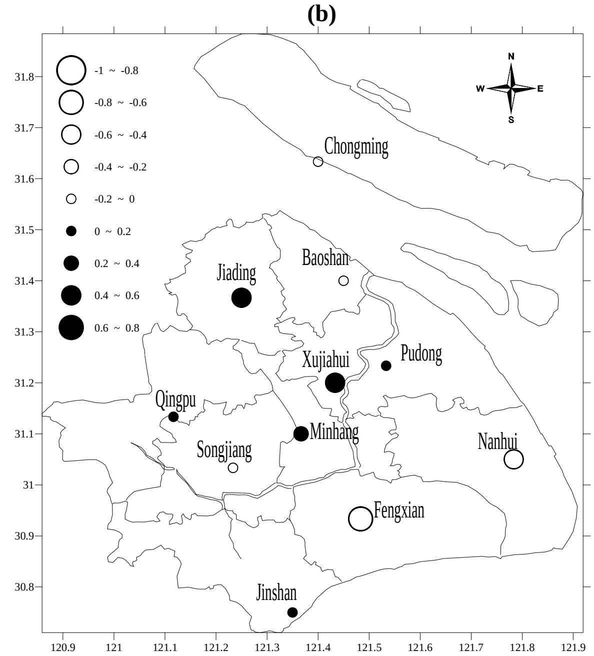


(d)



(c)

Figure 6. Same as Figure 3 but for the distribution of relative rainfall during winter (a/b) and summer (c/d) for the period of 1960-1983 and 1984-2007.

7 CONCLUSIONS

In this study, different characteristics of precipitation distribution under different urbanization stages are investigated with the approach of spatial standard deviation and the major results are summarized as follows.

(1) Inhomogeneous spatial distributions of annual rainfall in Shanghai are in close association with the urbanization. Spatial differences of the annual rainfall increase with the differences in urbanization between the central districts and the suburbs.

(2) Temporal and spatial distribution patterns of rainfall in Shanghai vary with the urbanization pace. During the rapid urbanization, both annual precipitation and rainfall strength are concentrated in the central districts. The days of heavy rainfall stronger than rainstorm, instead of the days of annual total rainfall, exhibit clear features of urban rainfall island, but they are not significant in the slow period of urbanization. As far as different seasons are concerned, speed of urbanization exerts insignificant influences on the spatial distribution of rainfall during winter and spring. On the contrary, rainfall during summer and autumn (especially summer) shows distinct features of urban rain-island features during the rapid urbanization.

(3) Changes of spatial distribution for the trend of annual rainfall also take place during different periods. Variations of annual rainfall exhibit consistent trends over the Shanghai region for the slow urbanization. However, inconsistent spatial distributions of the variation have taken place over the central districts

and suburbs of Shanghai during the rapid stage. The annual rainfall amount over the central districts has an increasing trend while that in the suburbs shows a decreasing trend after the speeding-up of urbanization.

Remarkable urban rain-island features of summer rainfall over the Shanghai region during the rapid urbanization may be related to favorable conditions of the central districts, which include local atmospheric convergence and ascending motion, as well as numerous condensation nuclei and city’s obstacle effect on the rainfall system[20]. On the other hand, the distribution pattern of winter precipitation in Beijing has converted from an “urban rain island” in the slow urbanization period to an “urban dry island” in the fast urbanization period[19]. Under the condition of limited water vapor during winter in Beijing, large amount of cloud nuclei over the central districts are not favorable to the enhancement of cloud drop and precipitation. Therefore, the difference in water vapor condition between winter and summer may contribute to differences between the spatial patterns of summer rainfall in Shanghai and those of winter precipitation in Beijing. The mechanisms for the large differences in precipitation distribution patterns between Shanghai and Beijing, two fast urbanized metropolises in China, need to be investigated in reference to the preliminary discussions presented above.

Acknowledgement: The authors would like to thank Prof. ZHANG Jin from National Climate Center and Dr CHEN Bao-de from Shanghai Typhoon Institute for their valuable suggestions.

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Citation: LIANG Ping, DING Yi-hui, HE Jin-hai et al. Study of relationship between urbanization speed and change of spatial distribution of rainfall over Shanghai. *J. Trop. Meteor.*, 2013, 19(1): 97-103.