Hourly Extreme Precipitation Changes under the Influences of Regional and Urbanization Effects in Beijing

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Abstract

Short duration extreme precipitation has devastating Impacts on city area. Local urbanization effects, superimposed upon regional climate change, complicate examination of long-term changes in short duration precipitation extremes in urban areas. Based on high-quality rain gauge observations of summertime hourly precipitation in Beijing Region over 1977-2013, this study reveals that despite the general drying tendency for North China, the urban area of Beijing has experienced more hourly precipitation extremes (HPE) than the suburban area since 2004, coinciding with the surge in the growth of urban built-up areas. These hourly urban precipitation extremes are increasingly inclined to occurring during nighttime (18:00LST to 02:00LST). On the one hand, the amplified urban heat inland effect, which was more significant at nighttime, seems to have facilitated formation of more intense small scale thermal-low and resultant ascending branch; on the other hand, it has favored to establishing unstable stratification in the lower level. This possible mechanism explains the preference of hourly precipitation extremes in urban areas during nighttime and climate change diversity under the influence of megacity superposition.

1. Introduction

In the past few decades, climate change research has mainly focused on global or regional scales. As a matter of fact, city climate change issues are receiving more and more attention worldwide. The Intergovernmental Panel on Climate Change (IPCC), starting with the Sixth Assessment Report (AR6), is paying more attention to regional issues of climate change and urban sustainable development issues in conjunction with the Paris Agreement. Thus, current climate change research should consider the overlapping influences of global, regional, and urban effects for the cities (Zhai et al., 2019).

Due to its damaging consequences and complex mechanism, extreme precipitation has always been one of the hottest issues in climate change research. It has received considerable attention from news media and the general public. Though a large body of literature has reported changes in multiple properties of precipitation extremes, most attention has been devoted to daily-scale events. As increasing regions have witnessed devastating flash floods, analysis and framing of questions in terms of sub-daily precipitation extremes are becoming more critical (Trenberth, 2011). In China, some previous researches have revealed that changes in extreme precipitation at different time scale exhibit distinct rationality. Generally, in North China, frequency of short-duration extreme precipitation decreased but intensity increased, while in southern China, especially in the Yangtze River Valley, frequency and amount increased (Zhang and Zhai, 2011).

The impact of sub-daily precipitation extremes is manifested most obviously in densely-populated and economically-developed areas, such as megacities, where both the vulnerability and exposure to precipitation-induced disasters are very high (Willems *et al* 2012). Various aspects of sub-daily precipitation extremes, including the frequency, intensity and duration, have been investigated in different regions of the world (Beck *et al* 2015, Chan *et al* 2014, Mishra and Mishra 2014). Nonetheless, most of them just considered the regional effects, few of them have placed these changes under the context of urbanization overlapped, which was considered as a factor to influence precipitation extremes in a significant and measurable manner (Wang and Zhai 2009, Pathirana *et al* 2014, Song *et al* 2014, Li *et al* 2015). Although to a certain degree extreme precipitation is greatly affected by large-scale circulation, local climate impacts induced by urbanization cannot be ignored, especially in strong convective precipitation. In theory, three primary effects of urbanization are potentially attributable in altering the intensity and frequency of precipitation, i.e. urban heat island effects (UHI) (Jauregui and Romales 1996, Bornstein and Lin 2000, Dixon and Mote 2003), urban canopy effects (Chen *et al* 2011, Miao *et al* 2011), and urban aerosol effects (Guo and Coauthors 2014, Jin *et al* 2005). It may be more obviously punctuated in China, where urbanization is unprecedentedly fast, particularly in some megacities like Beijing. As a result, short duration precipitation extremes in such megacities are capable of inducing severe waterlog or even devastating flooding. A case in particular is the record-breaking event hit Beijing on 21st July 2012, when the maximum hourly amount reached 85mm. Just in a few hours, this event completely paralyzed the entire urban area of Beijing, and caused 79 casualties along with huge financial losses (Zhang *et al* 2013). By contrast, whether changes in hourly precipitation extremes occurred in commensurate with rapid urbanization processes has been rarely inspected. That's the very purpose of this study. This study will take Beijing as an example to shed some light on this interesting topic under the precipitation background of North China. Three steps have been taken: Step 1, comparison of total summer precipitation and HPE between Region Beijing and North China; Step 2, changes of summer extreme precipitation between Suburban and Urban areas in Region Beijing; Step 3, potential urban effects on summer extreme precipitation in highly developed areas. Relevant methods and matrix could also be applied in investigating the relationship between urbanization and hourly precipitation extremes in other parts of the world.

2. Data and methods

Data. We obtained summertime (June-August) hourly precipitation data of 178 stations within North China from the National Meteorological Information Center (NMIC) under China Meteorological Administration (CMA) and a dense network of 18 stations in the Beijing area (See Figure 1a and Figure 1b). Before being released, this dataset was subject to strict quality controls by the NMIC (Yu *et at* 2007). To further minimize influences of missing values on trend estimations, only stations with missing records less than 5% in each summer were retained. Apart from precipitation data, 6-hour observations of 2-m temperature and surface pressure data were also employed to give preliminary physical explanations. In addition, 850hPa prevailing wind field analyses in this study are used daily zonal and meridional winds at 850 hPa from the ERA-Interim dataset with a resolution of 0.125° by 0.125° over the period 1977–2013.

In order to distinguish urban area from suburban ones objectively and properly, satellite image data from the US Defense Meteorological Satellite Program (DMSP)/ Operational Linescan System (OLS) is utilized. The DMSP/OLS nighttime light images reflect comprehensive information, which covers the traffic roads, residential areas and other built-up areas. The value range of DMSP/OLS nighttime light images is 0-80. Generally, the value above 55 can be regarded as urban areas. Therefore, this data provides the scientific basis for the research of this study (Imhoff *et al* 1997). In addition, the observation stations are divided into three types: urban area, suburban area and mountain area (Figure 1b).

The built-up area index of Beijing is obtained from *Beijing statistical yearbook* (*Beijing statistical yearbook* is an annual book published by China Statistical Press) and this index is used to reflect the rapid development of the urban area.

Methods. The 95th percentile is used to delimit hourly extreme precipitation events (HEPs), and the threshold was calculated by using all hourly records gathered during the period from 1981 to 2010, a normal period (a standard reference period of 30 years defined by WMO). With the defined threshold, the HEPs changes are based on derived information covering the entire period during 1977-2013. The threshold information for each station is shown in Table s1.

The UHI effect is measured as the difference of mean temperature among the urban and suburban stations. The same method is utilized to calculate the difference of sea level pressure (SLP) between urban and suburban areas. This station classification in Region Beijing is similar to the research studied by Wang *et al* (2012) and Wang *et al* (2013).

3. Results

3.1 **Changes in Hourly Extreme Precipitation in North China and Beijing**

Previous studies indicate that extreme daily precipitation exhibit an obvious increasing trend in most part of China in past decades, but in North China, recent studies show that there is no obvious trend or even a decreasing trend (He and Zhai, 2018).The region of North China is vast and has a complex terrain, with rolling mountains and vast plains, leading to marked disparities in local climate. In this study, we investigated changes in summer total precipitation and extreme precipitation in Region Beijing and North China, attempting to reveal the connections and differences in hourly extreme precipitation in Beijing and North China.

Figure 2a-b displays that inter-annual variability in both summer total precipitation and hourly extreme precipitation in Region Beijing and whole North China are in very similar patterns. The correlation coefficients for total precipitation and hourly extreme precipitation in Region Beijing and North China are 0.82 and 0.81, respectively. As shown in Figure 2a and Figure 2b, changes in amounts of summer total precipitation and HEP in Region Beijing and North China all displayed decrease trends. Before 2000, change in HEP did not see obvious trends in both. Since then, however, total summer precipitation and HEP in both Region Beijing and North China has increased, and such trend is more obvious in HEP in Region Beijing.

Relatively, the contribution of extreme precipitation to total precipitation in summer over North China displayed a slight increasing trend before 2000, but no obvious trend for Region Beijing.

Comparatively, contribution of extreme precipitation to total summer precipitation before 2000 in North China displayed a slight increase trend, but no obvious trend in Region Beijing. Since 2000, this kind of contribution in Region Beijing has become more rapidly increased as compared to North China (Figure 2c). It clearly shows that change precipitation structure has changed differently for North China and Region Beijing since 2000. The above results suggest that under the general precipitation decrease background in North China, extreme precipitation and its contribution to total precipitation in Region Beijing have increased, it may related to the rapid urbanization. The following analyses will focus on urbanization effect on hourly precipitation extremes in Region Beijing, in which the urban and suburban areas are separately studied.

3.2 Connection between Hourly Extreme Precipitation and Urbanization

In order to study the impact of urbanization, it is necessary to distinguish the urban area and suburban area in Region Beijing and an objective classification method is applied in this study. In a comprehensive accounting for topography and light distribution, identified urban stations (black dots), mountain stations (green dots), and suburb stations (blue dots) are shown in Figure 1b. In order to distinguish the impact of terrains, this paper chooses urban and suburban areas for a comparative analysis.

After counting the hourly precipitation extremes (HPE) occurrences of each site per year in Region Beijing, we analyzed the changing features of HPE in urban, suburban and mountain areas. The results are shown in Figure s1. There are distinct differences among three areas (see Figure s1d), which indicates that different underlying surface may have an impact on HPE. To further extract spatial patterns (coherent or contrasting), the EOF method is first performed with respect to the frequency of HPE to extract spatial patterns. As indicated in Figure 3, the first mode portrays a pan-Beijing pattern, with its variance contribution of 53% (Figure 3a-b). Judged by its time coefficient, this pattern is more typical of a decadal-scale oscillation, which is characterized by reduced occurrences of HPE during 1995-2000 and a subsequent recovery since 2000. This mode may reflect the spatial coherence characteristic of HPE in whole North China. The changing characteristic is consistent with the extreme precipitation shown in Figure 2b. The correlation coefficient between variation of precipitation in North China and the first mode time series for EOF1 of Region Beijing is 0.8, and it also evidenced spatial coherence of HPE changes for Beijing under the larger regional background.

Interestingly, the contrastive variations among stations shown in the second mode resemble the spatial distribution of urban and suburban stations (including mountain stations) judged by light image data. Therefore, the second mode of the EOF analysis could be used to explore the influences of urbanization on HPE in Region Beijing, as the trend of HPE shows a decreasing trend in suburbs which is opposite to urban area (Figure 3c-d). This mode shows that under the influence of the urbanization, the precipitation in the urban area has changed differently from the surrounding area. Someone may question if EOF3 time coefficient really reflect the contrast feature between urban and suburban areas. To further test this, we have classified suburban areas into four different suburban station groups: a) the area with 3 stations in the northeast plain suburb (NSA); b) the area with 2 stations in the south suburban area (SSA); c) the area with 3 stations in the mountain region of the northwest suburban area (MA); d) all of the 8 stations in the suburb to ensure using all suburban stations around the core urban area (ALL). The result is shown in Figure 4. In the figure, we can see the only difference is found in the south suburban area （SSA）at the upper stream of prevailing wind direction. The northern areas and all suburban stations collectively reflect the same long term change feature as the 3 representative stations mostly used in this study. This proves that the suburban stations selected in this study are representative in calculating urban-suburban difference in HEP changes.

The pattern of third EOF mode has almost the same variance contribution as that of the second one. The third mode highlights the opposite variations between southeastern and northwestern parts of Region Beijing (Figure 3e-f). This pattern may deliver more information about influences of topography on HPE. Regarding the influence of terrain on precipitation, on the windward side, forced lifting of air masses triggers condensation and precipitation with increasing elevation. Topography strongly influences precipitation patterns by altering both the local wind patterns and the condensation of precipitable water (Siler and Roe, 2014). In North China, short-duration rainfall events during warm season are mainly observed in the southeastern inner periphery of the Taihangshan and Yanshan Mountains. The topography could influence diurnal variations of surface temperature, moisture, and wind fields, to initiate rainfall events over the northwestern mountains (Yuan et al., 2014). Case study for extreme rainfall event in Beijing revealed that the observed extreme rainfall was mostly generated by convective cells that were triggered by local topography and then propagated along a quasi-stationary linear convective system into Beijing (Zhang et al, 2013). Potentially, interactions of UHI-induced flow with topographically induced flow in initiating or enhancing convection can be also important. It is worthy for further study in the future.

To focus on connection between HPE and urbanization, index measuring built-up areas in Region Beijing was adopted from the Beijing statistical yearbook. The difference of HPE occurrences between urban and representative suburban area in the northeast suburban plain is plotted in Figure 5a. After a gradual expansion of urban area, built-up areas in Beijing experienced unprecedented growth after 2000 and it reached a new peak since 2004. Coincidently, a conspicuous regime shift of precipitation index also occurred around this period before 2004, when there are more HPEs in suburban area. This is because airflow is likely to cause more precipitation in the suburbs. There are many observational studies indicating that precipitation is enhanced downwind of urban areas (e.g., Shepherd and Burian, 2003, Earth Interactions). To further investigate if such enhancement also can be seen Region Beijing, the prevailing wind fields in the two periods before and after 2004 in North China are presented in Figure 6. It is obvious that most of the studied area is dominated by southwesterly winds. The northeast suburb of Beijing is just at the downwind side of the City. Climatologically, the summer precipitation in the northeast suburban area is more than that in other parts of Region Beijing. However, in this study, it is found that short-duration extreme precipitation has been enhanced more in the city area than the downwind side of northeast suburban area.

As shown in Figure 5a, a transitional change indicates more HPEs concentrating in the urban area after dramatic expansion of built-up area after 2004. Actually, such reversal of HPEs in urban and suburban areas since 2004 also matches well with time coefficient in EOF2 analysis (Figure 3d). This further enhances the connection between the rapid urbanization and the drastic increases of urban HPEs. What condition was changed with the expansion of urbanization? The dramatic factor is air temperature, and the changes in maximum air temperature of the date when HPE occurs are given in Figure 5b. Astoundingly, the temperature condition for those days with HPE occurrence is also changed after 2004, which is consistent with the regime shift of HPE between urban and suburban areas.

The usage of hourly precipitation data also enables us to unearth some masked characteristics in analyses based on daily extremes, particularly for occurrence timing and diurnal cycle of hourly extremes. As revealed in Figure 7, HPEs tend to occur during the period especially in night-time from evening to nighttime (18:00LST-02:00LST) for urban area in recent decades as compared to suburbs. The relative trend is statistically significant at 95% confidence level. Such preference in occurrence timing is predominately determined by local rainfall diurnal cycle as reported by Li *et al* (2008), based on climatology of one station observations. Before

2004, HPEs occurred more frequently in suburban areas, especially during nighttime. Thereafter, nighttime HPEs shifted towards urban areas.

3.3 Potential Mechanism

In view of the above-mentioned facts, there indeed exists linkage between urbanization and changes in HPE. However, is there any causation behind this linkage or does it only represent certain coincidence? We attempt to explain this from both dynamic and thermodynamic aspects. The air temperature difference may be a non-negligible factor. As shown in Figure 8a, Urban Heat Island (UHI) has exhibited a significant increasing trend, with the UHI index over 1°C after 2004, the maximum temperature difference can even be up to 12°C. The strengthening of UHI effects shows larger magnitude during nighttime. The diurnal cycle of UHI reveals that UHI is clearly stronger between 20:00 local solar time (LST) and 02:00 LST, while weaker during daytime. The difference of UHI between nighttime and daytime is becoming larger and larger in recent decade. Significantly enhanced heating effects of UHI in urban area resulted in more frequent occurrences of thermal low in urban areas, evidenced by decreased sea level pressure (SLP) during the past few decades (Figure 8b). The difference of SLP between urban areas and suburbs (urban minus suburban) fluctuates around zero value line before 2004 but it suddenly exhibits a dramatic decreasing trend since 2004. This indicates that the difference of SLP between urban and suburban areas is more significant after the rapid urbanization, especially at night time. To further support the above explanation, we provided Figure 9 showing the pattern of near-surface wind changes overlapped with SLP difference in the Beijing area. In this figure, it clear that the surface winds converge from the suburbs to the city center. Since the surface winds in the city is greatly affected by surface friction, it is difficult to perfectly reflect low-level convergence by using directly observed surface wind data. Nevertheless, with the support of surface pressure data as reflected in Figure 8a, it is very likely that the enhanced thermal convection activities are associated with intensified heat island effect.

Such result was also suggested by Lu and Arya (1995) for other cities based on model studies. Above discussed changes in thermal and dynamical conditions would likely alter local circulations between urban and suburban areas. More specifically, during nighttime it might enhance ascending branches and then tend to dominate in urban areas, accompanied by descending branch covering suburban areas. In addition to favorable dynamical driver, warmer underling surface in urban area during nighttime would also be favorable to establishing an unstable layer, which facilitates more heavy precipitation events in urban areas. Corresponding to the urban heat island effect, the relative humidity also has diurnal cycle characteristics. The atmospheric water vapor in urban areas of Beijing is obviously higher during nighttime as compared to daytime (Liu et al., 2009) .

Table 1 shows the average of the HPEs, UHI, and the difference of SLP between urban and suburban areas during the period before 2004 and that after 2004, respectively. All results are statistically significant at the 95% level, which illustrates how meteorological factors have significantly changed by the rapid urbanization.

4. Summary and Discussion

This study reveals the differences in changes in hourly precipitation extreme between the urban and suburban of city Beijing in the context of regional change in North China. Possible mechanism behind has also been discussed. Main conclusions are as follows.

(1) Against the general background of decreasing precipitation in North China over the past few decades, the hourly extreme precipitation contribution to total precipitation in Region Beijing has increased. This means that short- duration extreme precipitation has intensified in Region Beijing in summer.

(2) Further analyses reveal that along with the rapid urbanization, urban area of Beijing has witnessed relatively increased occurrences of hourly precipitation extremes as compared to the suburban area during the period of study. Such increase is very prominent since 2004 when Beijing has experienced drastic urbanization.

Interestingly, short-duration extreme precipitation has become more frequent especially during night-time in the urban.

(3) As part of causality, the rapid urbanization has amplified the urban heat island effect, which is more significant at night. This has facilitated formation of more thermal-low and resultant ascending branch, as well as established unstable stratification in the lower level, and thus triggered more favorable conditions conducive to extreme precipitation in the urban area than the suburb. In the other studies, Oke et al. (2017) also suggested the air temperature difference between urban and suburban areas has become larger because suburban area cools more rapidly than the city in the night-time, and then induce thermodynamically driven small-scale flows.

In the past few decades, studies indicated the daily extreme precipitation and total precipitation have decreased in North China in summer-time. Benefit from valuable high-resolution data, this study reveals that at hourly time scale, extreme precipitation has not decreased and its contribution to the total precipitation has even increased, especially in Region Beijing. Such phenomenon suggests that precipitation event has become dominated by short-duration extreme precipitation in a warming climate in North China. Increasing urbanization in City Beijing has further enhanced short-duration extreme precipitation process.

An UHI can induce moist convection and thus precipitation, but the precipitation amount is not determined solely by UHI intensity. The intensity of convection or precipitation depends on many other factors including thermodynamic instability, wind shear, and aerosol number concentration, etc. The interaction between surround environment and mega-city is an important research topic. City Beijing is next to the mountains in the west and north. The interaction between the mountains and urbanization and influence on climate of City Beijing requires further research in the future.

Recent numerical modeling studies show that the relationship between precipitation amount and aerosol loading is not monotonic (Jeon et al., 2018; Lkhamjav et al., 2018). The amount of precipitation from deep convective clouds slightly decreases as aerosol loading increases in a certain range of concentration, while notably increases in a higher concentration range. As for city Beijing, primarily statistics suggested that slight decreasing trends of annual mean PM10 and PM2.5 were observed since 2000 (Liu et al., 2014). Whether such a decreasing aerosol change has played any crucial role in changing precipitation in Beijing is an important scientific issue to further address.

The influence of urbanization on extreme precipitation is highly complex, especially in Beijing. The combination influences of heat island effect, topography, small-scale hydrological process and aerosols are very complicated processes for urban precipitation. In the future studies, efforts should be more devoted to combination influences of multiple factors on short-duration precipitation extremes to provide insight into mechanisms of the urbanization impact on city climate and impacts in the context of global warming.

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Reference

Beck F, Bárdossy A, Seidel J, Müller T, Sanchis E F and Hauser A 2015 Statistical analysis of sub-daily precipitation extremes in Singapore *J. Hydrol.* **3** 337-358

Bornstein R and Lin Q 2000 Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies *Atmos. Environ.* **34** 507-516

Chan S C, Kendon E J, Fowler H J, Blenkinsop S and Roberts N M 2014 Projected increases in summer and winter UK sub-daily precipitation extremes from high-resolution regional climate models *Environ. Res. Lett.* **9** 084019

Chen F, Kusaka H, Bornstein R, † J C, Grimmond C S B, Grossman-Clarke S, Loridan T, Manning K W, Martilli A and Miao S 2011 The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems *Int. J. Climatol.* **31** 273-288

Dixon P G 2003 Patterns and Causes of Atlanta's Urban Heat Island-Initiated Precipitation *J. Appl. Meteor.* **42** 1273-1284

Guo J, Deng M, Fan J, Li Z, Chen Q, Zhai P, Dai Z and Li X 2014 Precipitation and air pollution at mountain and plain stations in northern China: Insights gained from observations and modeling *J. Geophys. Res.* **119** 4793-4807

Guo J , Su T , Li Z , et al. Declining frequency of summertime local-scale precipitation over eastern China from 1970 to 2010 and its potential link to aerosols[J]. Geophysical Research Letters, 2017, 44(11):5700-5708.

Han J Y, Baik J J and Lee H 2014 Urban impacts on precipitation Asia-Pacific *J. Atmos. Sci.* **50** 17-30

He B R, Zhai P M.Characteristics of the persistent and non-persistent extreme precipitation in China from 1961 to 2016. Advanced in Climate Research. 2018, Vol. 14 (5): 437-444

Imhoff M L, Lawrence W T, Stutzer D C and Elvidge C D 1997 A technique for using composite DMSP/OLS “city lights” satellite data to map urban area *Remote Sens. Environ.* **61** 361-370

Jauregui E and Romales E 1996 Urban effects on convective precipitation in Mexico city *Atmos. Environ.* **30** 3383-3389

Jeon Y L , Moon S , Lee H , et al. Non-Monotonic Dependencies of Cloud Microphysics and Precipitation on Aerosol Loading in Deep Convective Clouds: A Case Study Using the WRF Model with Bin Microphysics[J]. Atmosphere, 2018, 9(11).

Jin M, Shepherd J M and King M D 2005 Urban aerosols and their variations with clouds and rainfall: A case study for New York and Houston *J. Geophys. Res.* **110** 211-211

Lemonsu A, Viguié V, Daniel M and Masson V 2015 Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France) *Urban Clim*. **14** 586-605

Li D and Bou-Zeid E 2013 Synergistic Interactions between Urban Heat Islands and Heat Waves: the Impact in Cities is Larger than the Sum of its Parts *J. Appl. Meteorol. Clim*. **52** 2051-2064

Li J, Yu R and Wang J 2008 Diurnal Variation of Summer Precipitation in Beijing

Chin. Sci. Bull (*in Chinese*). **7** 829-832.

Li Q, Li W, Si P, Gao X, Dong W, Jones P, Huang J and Cao L 2010 Assessment of surface air warming in northeast China, with emphasis on the impacts of urbanization *Theor. and Appl. Climatol.* **99** 469

Liu, W. , You, H. , & Dou, J. . (2009). Urban-rural humidity and temperature differences in the beijing area. Theoretical and Applied Climatology, 96(3-4), 201-207.

Liu Z , Hu B , Wang L , et al. Seasonal and diurnal variation in particulate matter (PM10 and PM2.5) at an urban site of Beijing: analyses from a 9-year study[J]. Environmental ence & Pollution Research, 2015, 22(1):627-642.

Lkhamjav J , Lee H , Jeon Y L , et al. Impacts of Aerosol Loading on Surface Precipitation from Deep Convective Systems over North Central Mongolia[J]. Asia-Pacific Journal of the Atmospheric Sciences, 2018, 54(4):587-598.

Lu J and Arya S P 1995 A Laboratory Simulation of Urban Heat-Island-Induced Circulation in a Stratified Environment pp 405-429

Miao S, Chen F, Li Q and Fan S 2011 Impacts of Urban Processes and Urbanization on Summer Precipitation: A Case Study of Heavy Rainfall in Beijing on 1 August 2006 *J. Appl. Meteorol. Clim.* **50** 806-825

Mishra P and Mishra V 2014 Projections of sub-daily precipitation extremes in major global urban areas AGU Fall Meeting

Oke T R. City size and the urban heat island[J]. Atmospheric Environment, 2017, 7(8):769-779.

Parker D E 2010 Urban heat island effects on estimates of observed climate change *Wiley Interdiscip. Rev. Clim. Change* **1** 123–133

Pathirana A, Denekew H B, Veerbeek W, Zevenbergen C and Banda A T 2014 Impact of urban growth-driven landuse change on microclimate and extreme precipitation — A sensitivity study *Atmos. Res.* **138** 59-72

Siler N , Roe G . How will orographic precipitation respond to surface warming? An idealized thermodynamic perspective[J]. Geophysical Research Letters, 2014, 41(7):2606-2613.

Song X, Zhang J, Aghakouchak A, Roy S S, Xuan Y, Wang G, He R, Wang X and Liu C 2014 Rapid urbanization and changes in spatiotemporal characteristics of precipitation in Beijing metropolitan area *J. Geophys. Res. Atmos.* **119** 11,250–11,271

Trenberth K E 2010 Changes in precipitation with climate change *Clim. Res.* **47** 123-138

Wang C C and Zhai P 2009 Changes of Precipitation Extremes in China's Large Cities *Climatic and Environmental Research (in Chinese)* **14**, 101-108.

Wang J, Yan Z W and Zhen L 2013 Impact of urbanization on changes in temperature extremes in Beijing during 1978-2008 *Chin. Sci. Bull.* **58** 4679-4686

Wang J, Zhang R and Wang Y 2012 Areal differences in diurnal variations in summer precipitation over Beijing metropolitan region *Theor. Appl. Climatol.* **110** 395-408

Willems P, Arnbjerg-Nielsen K, Olsson J and Nguyen V T V 2012 Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings *Atmos. Res.* **103** 106-118

Yang L, Tian F, Smith J A and Hu H 2014 Urban signatures in the spatial clustering of summer heavy rainfall events over the Beijing metropolitan region *J. Geophys. Res. Atmos.* **119** 1203–1217

Yu R, Zhou T, Xiong A, Zhu Y and Li J 2007 Diurnal variations of summer precipitation over contiguous China *Geophys. Res. Lett.* 34 223-234

Yuan W , Yu R , Chen H , et al. Topographic effects on spatiotemporal variations of short-duration rainfall events in warm season of central North China[C]// AGU Fall Meeting. AGU Fall Meeting Abstracts, 2017.

Zhai P, Zhang X, Wan H and Pan X 2005 Trends in Total Precipitation and

Frequency of Daily Precipitation Extremes over China *J. Climate* **18** 1096-1108

Zhai P,Yuan Y and Yu R. 2019 Climate change and sustainable development for cities. Chinese Science Bulletin, Volume 64, Issue 19: 1995-2001(2019)

Zhai Y, Guo Y, Zhou J, Guo N, Wang J and Teng Y 2014 The spatio-temporal variability of annual precipitation and its local impact factors during 1724–2010 in Beijing, China *Hydrol. Process.* **28** 2192–2201

Zhang D L, Lin Y, Zhao P, Yu X, Wang S, Kang H and Ding Y 2013 The Beijing extreme rainfall of 21 July 2012: "Right results" but for wrong reasons *Geophys. Res. Lett.* **40** 1426–1431

Zhang H, Zhai P . 2011 Temporal and spatial characteristics of extreme hourly precipitation over eastern China in the warm season. *Adv. Atmos. Sci.*, 28(5):1177-1183.

Zhen L I, Yan Z, Kai T U and Hongyi W U 2015 Changes of Precipitation and Extremes and the Possible Effect of Urbanization in the Beijing Metropolitan Region during 1960–2012 Based on Homogenized Observations *Adv. Atmos. Sci.* **32** 1173-1185

Zhu L, Chen Y, Yan R, Shen T, Jiang L and Wang Y 2012 Characteristics of Precipitation and Temperature Changes in Beijing City During 1951-2010 *Resources Science (in Chinese)* **34** 1287-1297

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Table 1. Average of HPEs, UHI and difference of SLP before and after 2004.

Item		Difference of occurrence in HPE	UHI(°C)			Difference of SLP(Pa)		
			Daily mean	2000LST	1400LST	Daily mean	2000LST	1400LST
Average Value	Period-1	-1.0	0.35	0.44	0.25	-10	-18	-1
	Period-2	1.5	0.85	1.0	0.54	-50	-64	-47

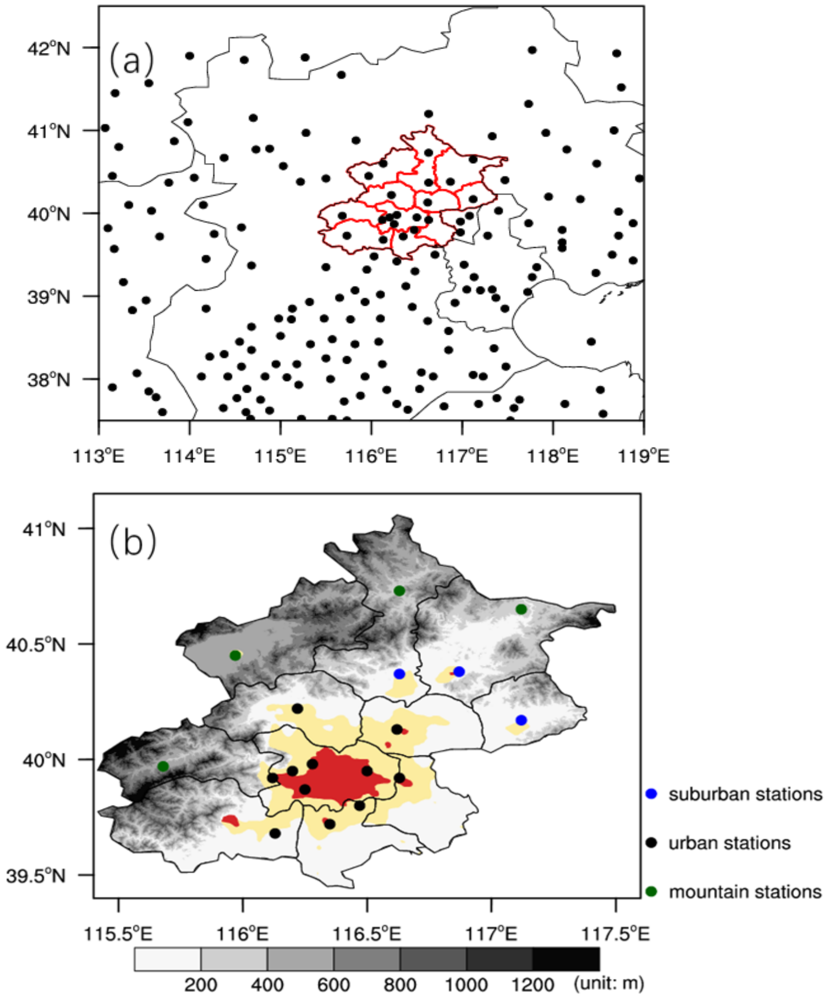

Figure 1. Distribution of rain gauge stations in North China and in Region Beijing**(a)**. 18 hourly observation stations in Region Beijing imposed on topographic, suburban and urban information. Grey to black shadings indicate topography (unit: m), and the red shaded areas represent built-up urban areas in 1992, whereas the yellow shaded areas indicate expanded built-up urban area in 2010 relative to 1992. Dots in green, blue and black represent the mountain, suburban and urban rain gauge stations, respectively (b).

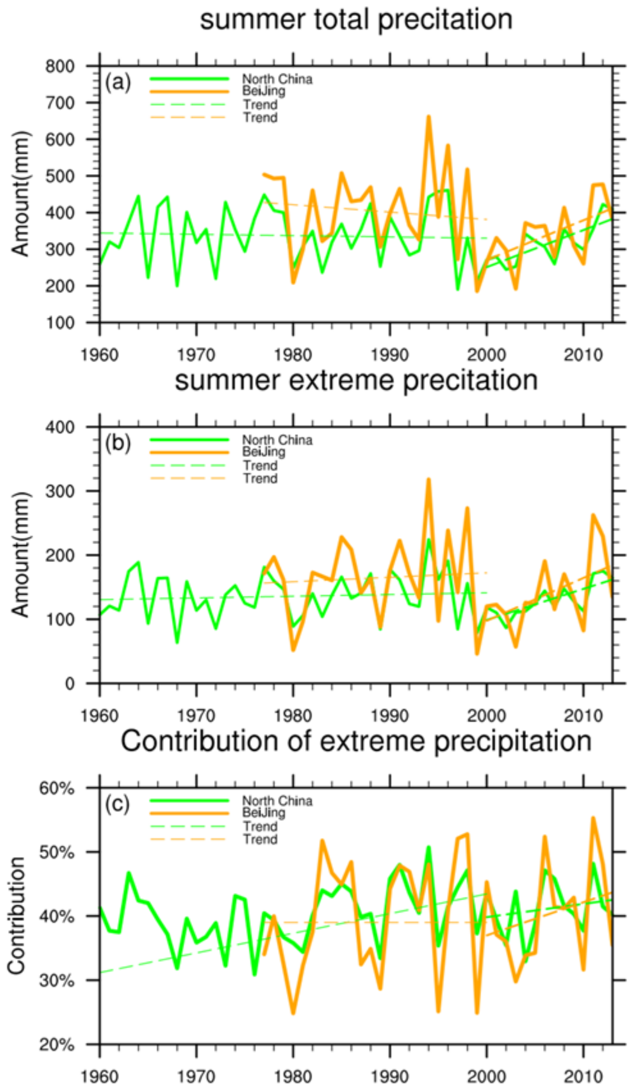

Figure 2 Changes in summer total precipitation (a); extreme precipitation (b); contribution of extreme precipitation to summer total precipitation(c).orange solid line represents the Beijing area and green solid line represents North China, dash lines indicate the trend for each period .

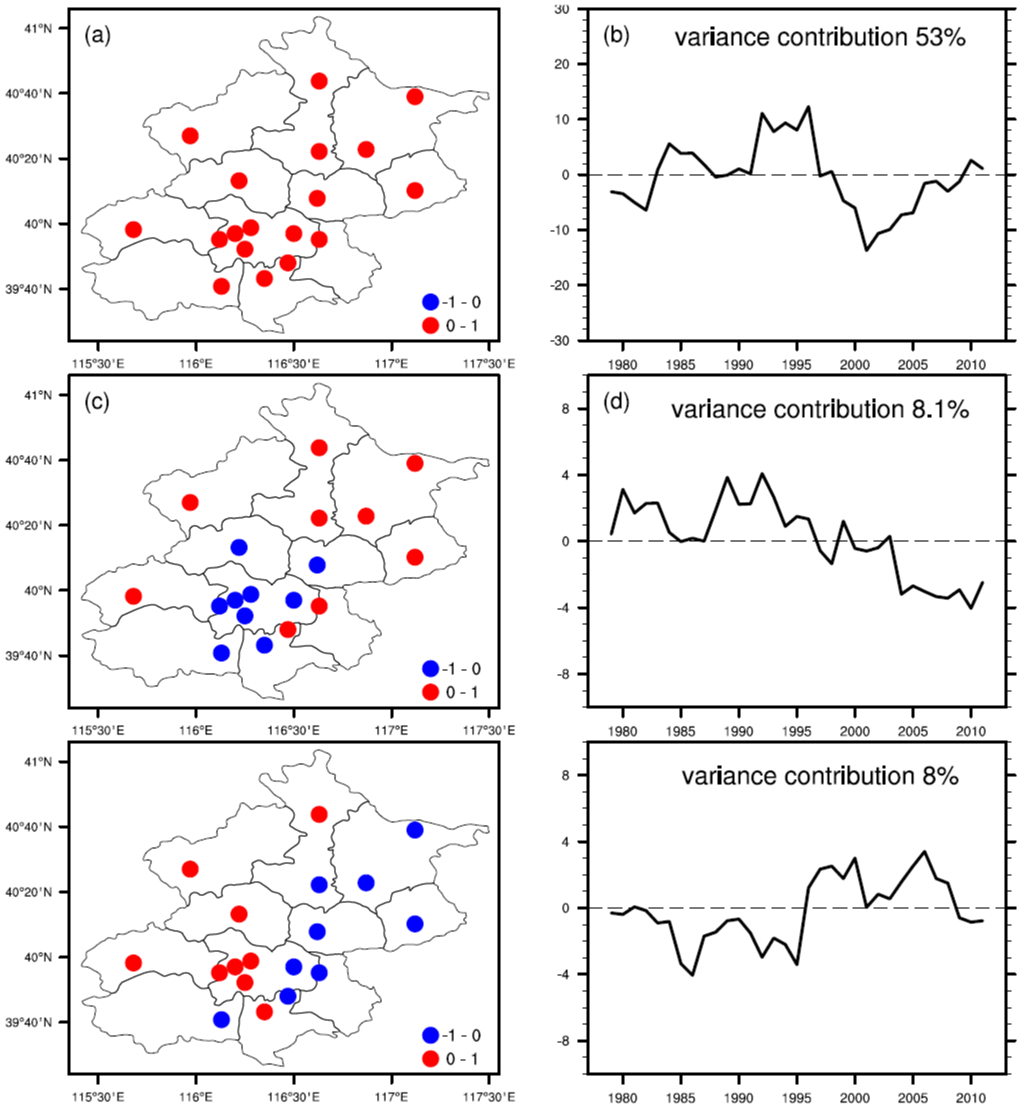

Figure 3. First three leading eigenvectors and their associated time series obtained from the EOF analysis of the occurrence frequency of hourly precipitation extremes (HPE) for the summertime (June through August) during the period from 1977 to 2013 in Beijing area. Positive and negative values are denoted by solid red and blue dots, respectively.

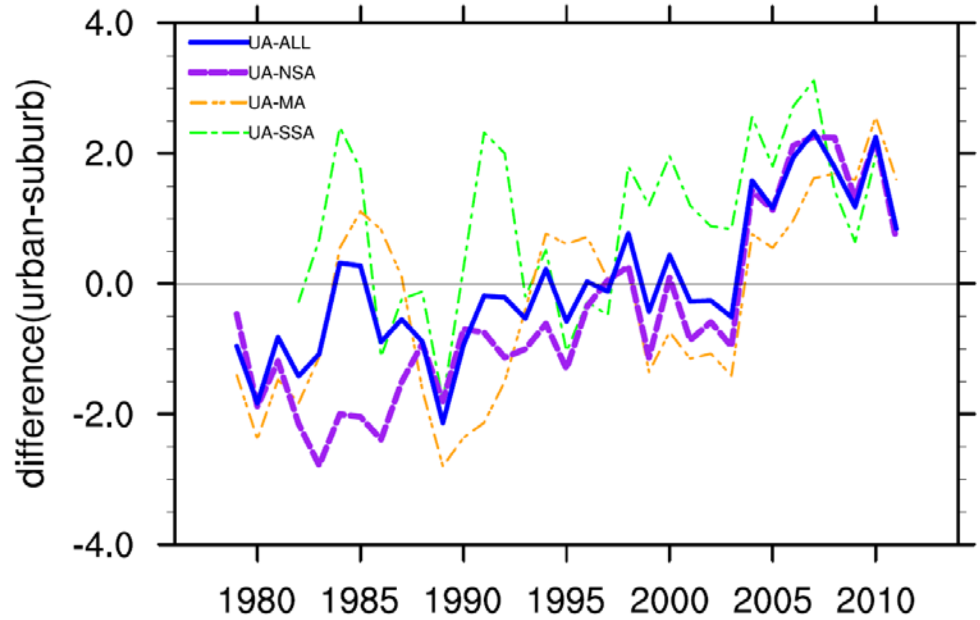

Figure 4. Comparison of differences in the hourly extreme precipitation occurrences between urban and various suburban area combinations for Region Beijing during the period from 1980 to 2013

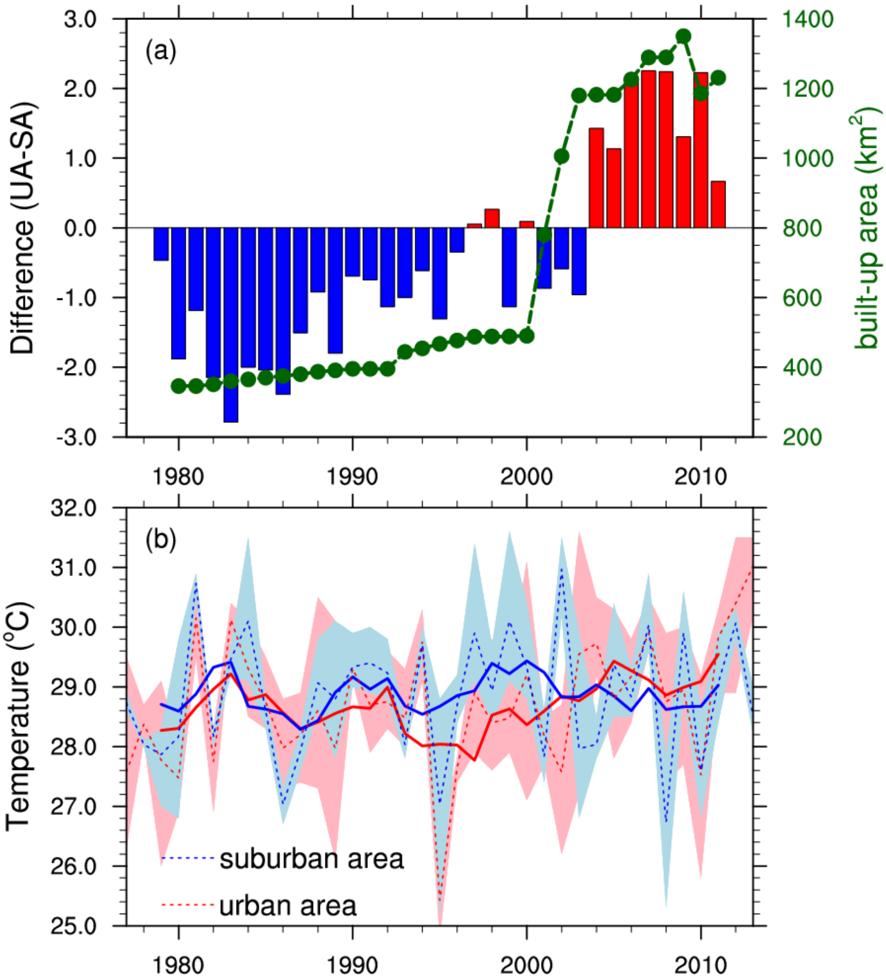

Figure 5. Temporal evolution of the hourly extreme precipitation occurrence differences (in blue and red bars) between urban and suburban rain gauges, and temporal evolution in built-up areas in Beijing during the period from 1980 to 2013 (dotted curve, unit: km^2) (a); changes in maximum air temperature of the date when HPE occurs (in red and blue dash lines) between urban and suburban areas, thick solid lines are 5-year removed and shadows mean fluctuation range (b).

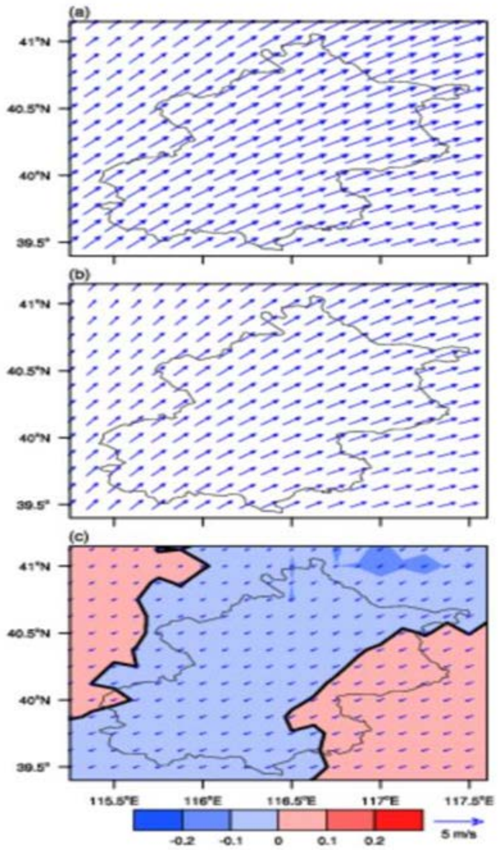

Figure 6. Summer-time winds distribution of 850-hPa in Region Beijing for the period 1977-2003(a) and 2004-2013(b), and their difference (c). Vectors are for winds and shaded areas with color reflecting difference of wind divergences.

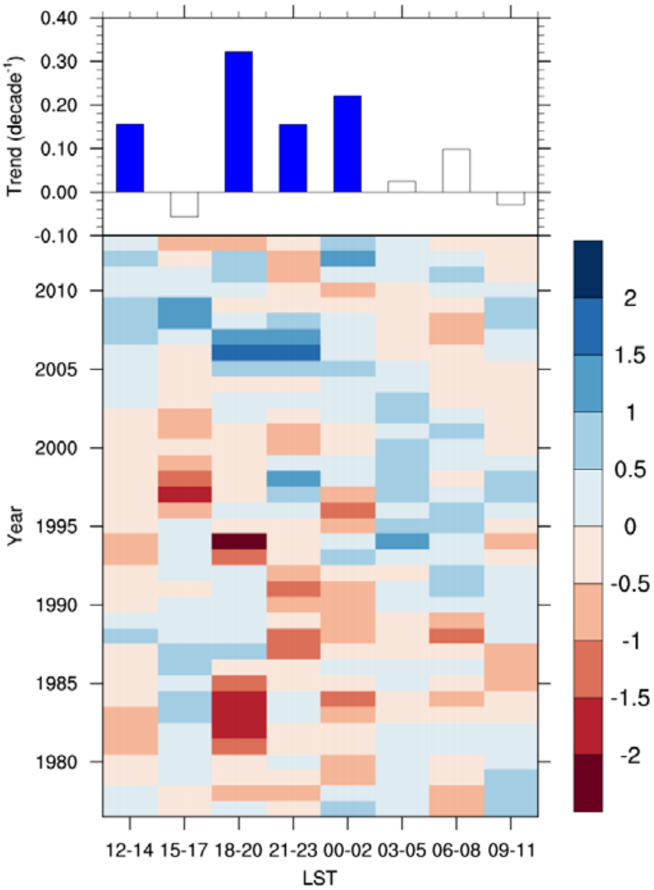

Figure 7. Temporal evolution of differences in summertime HPE occurrence frequency between Beijing urban and suburban areas over 1977-2013 (urban minus suburban) at different time periods of a day. Bars in the top panel show the trends of summertime HPE during 1977-2013 for the specific time periods of a day. Note that the red shaded bars indicate the trend is statistically significant at 95% confidence level.

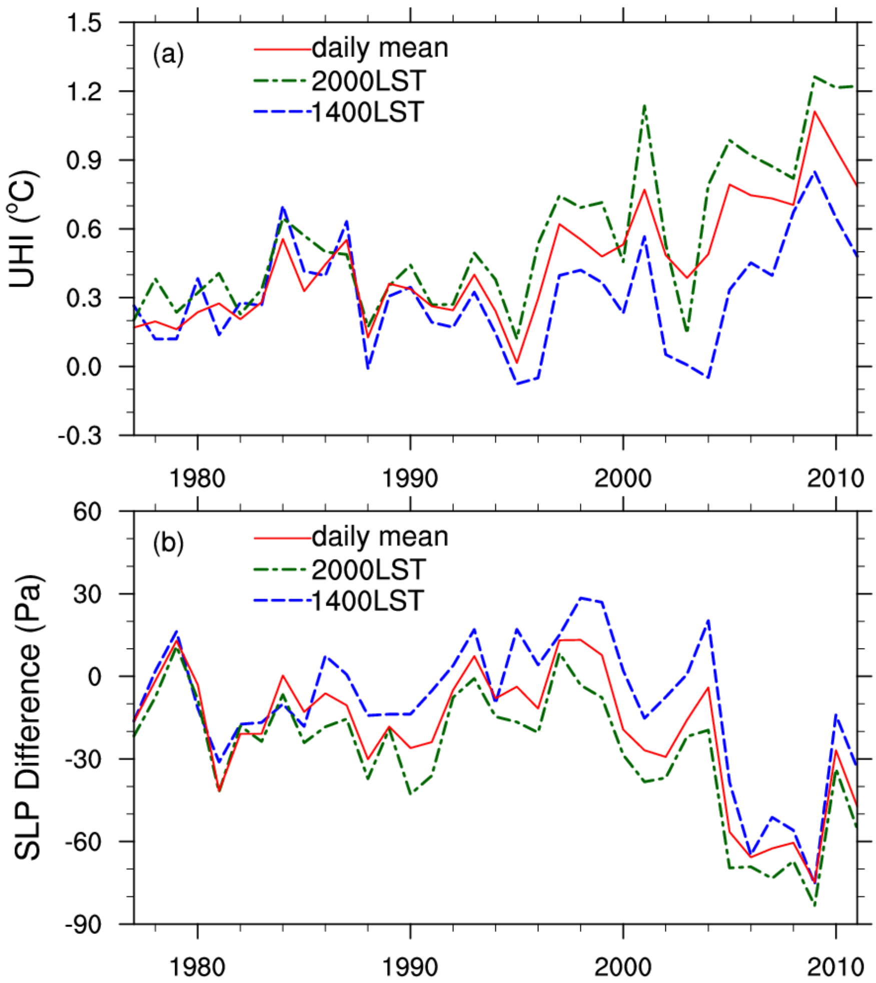

Figure 8. Annual variations of summertime urban heat island (UHI, in units of °C) for daily mean, 1400 LST, 2000 LST (a), and surface level pressure (SLP) differences (urban minus suburban, in units of Pa) for daily mean, 1400 LST, 2000 LST (b) in Beijing

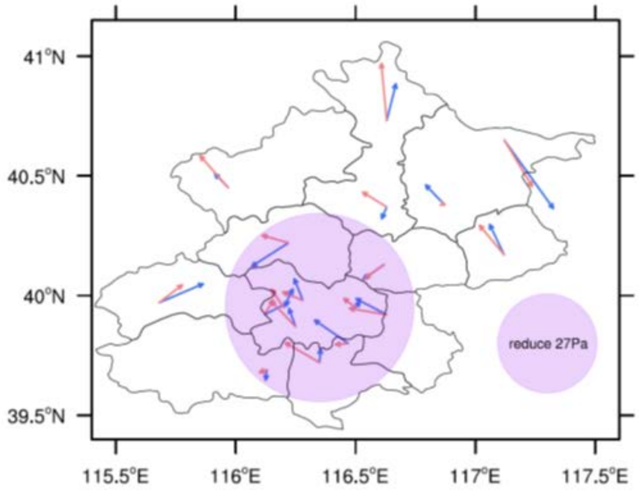

Figure 9. Distributions of surface winds at 18 stations in Region Beijing for the period 1977-2003 (blue arrow) and 2004-2013 (red arrow). The pink area represents the SLP difference between the two periods in the urban area.