

*Better knowledge with more gauges?
Investigation of the spatiotemporal
characteristics of precipitation variations
over the Greater Beijing Region*

Article

Accepted Version

Yang, W.-Y., Li, Z., Sun, T. ORCID: <https://orcid.org/0000-0002-2486-6146> and Ni, G.-H. (2016) Better knowledge with more gauges? Investigation of the spatiotemporal characteristics of precipitation variations over the Greater Beijing Region. *International Journal of Climatology*, 36 (10). pp. 3607-3619. ISSN 0899-8418 doi: 10.1002/joc.4579 Available at <https://centaur.reading.ac.uk/71093/>

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To link to this article DOI: <http://dx.doi.org/10.1002/joc.4579>

Publisher: John Wiley & Sons

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Better knowledge with more gauges? Investigation of the spatiotemporal characteristics of precipitation variations over the Greater Beijing Region

Journal:	<i>International Journal of Climatology</i>
Manuscript ID	JOC-15-0555.R1
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	01-Nov-2015
Complete List of Authors:	Yang, Wenyu; Tsinghua University, State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering Li, Zhe; Tsinghua University, State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering Sun, Ting; Tsinghua University, State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering Ni, Guangheng; Tsinghua University, State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering
Keywords:	Precipitation, Spatiotemporal characteristics, Beijing, Proper measurement method

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1 **Better knowledge with more gauges? Investigation of the**
2 **spatiotemporal characteristics of precipitation variations over the**
3 **Greater Beijing Region**

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21 Abstract

22 Using the hourly precipitation observations from 118 gauge stations and a weather
23 radar in the Greater Beijing Region (GBR) during 2008–2012, we investigate the
24 spatiotemporal characteristics of precipitation and discuss the appropriate
25 observational approach for capturing variability of precipitation over this region. In
26 general, the south central and northeastern GBR receives more intense precipitation
27 than other parts. The diurnal cycle of precipitation amount (PA) peaks in the evening
28 and decreases till noon, while precipitation intensity (PI) and precipitation frequency
29 (PF) both have two peaks. The stronger peaks of PI and PF occur in the evening while
30 the weaker ones appear in the early nighttime and in the afternoon. Remarkable
31 spatial heterogeneity also exists in the diurnal patterns of PA, PI and PF over the GBR.
32 Rainstorms extracted from radar data feature in short duration (11.4 hours in average)
33 and highly localized patterns (4.31–20.58 km / 1.85–9.10 km in major/minor radius
34 direction). The estimated diurnal cycles of PA, PI and PF are found to depend on the
35 gauge density in a sensitivity analysis, where a gauge density ratio of 0.6
36 (corresponding to 30 gauges in total with a representative area of 239.5 km² per gauge)
37 is identified as adequate to capture the temporal characteristics of precipitation in the
38 plain area of GBR. However, such gauge density ratio (i.e. 0.6) is incapable for
39 resolving the spatial characteristics of precipitation in GBR. As such, different
40 instruments (e.g. gauge network, weather radar, etc.) and multiple data sources are
41 suggested to be jointly utilized to better capture the characteristics of rainstorms in
42 GBR.

43 **Keywords:**

44 Precipitation; Spatiotemporal characteristics; Beijing; Proper measurement method

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65 1. Introduction

66 The spatiotemporal characteristics of precipitation hold the key for a better
67 understanding of the physical processes involved in hydrometeorology, especially for
68 those natural hazards linked with precipitation extremes, such as floods and landslides.
69 The variability of precipitation at different scales, either temporally from daily to
70 annual (e.g. Li et al. 2012; Yin et al. 2011; Yu et al. 2015), or spatially from local to
71 global (e.g. Li et al. 2014; Smith and Krajewski 1991), has been extensively
72 investigated. Among a variety of spatiotemporal scales, the precipitation variability at
73 the scale of sub-daily and ~10 km has been recognized for its critical role in
74 hydrometeorological processes: it not only helps to understand the physical processes
75 of precipitation formation (Dai et al. 1999a, 1999b), but also favors the evaluation of
76 numeric weather prediction (NWP) models in the precipitation forecasting (Wan et al.
77 2013; Yang and Smith 2006; Yang et al. 2014).

78 Precipitation variability analysis over contiguous China has been conducted on
79 sub-daily scales in recent years (e.g. Chen et al. 2009; Yin et al. 2009; Yu et al. 2007;
80 Zhou et al. 2008). It is found that the diurnal cycles of precipitation demonstrate
81 distinct regional features over contiguous China, while the causes of the differences
82 have not yet been fully discussed (Yu et al. 2007; Zhou et al. 2008), in particular for
83 the regions with complex topography and land cover (e.g. as discussed in
84 mountainous area by Li et al. 2014, and in urban area by Yin et al. 2011). Moreover, it
85 is found that the precipitation regimes over cities have been remarkably modified by
86 urbanization (Chen et al. 2011; Niyogi et al. 2011; Yang et al. 2013). Considering the

87 highly diverse urban surfaces, the severity of storm-induced floods in cities can be
88 worsen by the synergies between precipitation variability and landscape heterogeneity
89 (Yang et al. 2015). However, the spatial variability of precipitation in urban areas is
90 far from being well characterized maybe due to the limitation of the high-resolution
91 data (Westra et al. 2014). As such, there is an urgent need to investigate the
92 precipitation characteristics in cities on finer spatial scales (e.g. <10 km) (Berne et al.
93 2004).

94 Beijing, the capital of China with more than 21 million residents, has undergone a
95 rapid urbanization during the past three decades. Beijing is also a topographically
96 complex region, which is surrounded by mountains to its north, northwest, and west
97 and is highly urbanized in its eastern part. Situated at the northwestern part of the
98 North China Plain, Beijing is categorized into temperate monsoon climate zone and
99 characterized by frequent summertime heavy rainfall: the southeast monsoon brings
100 abundant water vapor from the Pacific Ocean; regional mountain-valley circulation
101 combined with land-use and land-cover change (LULC) facilitates local convection
102 and thus leads to the onset of summer rainstorm over Beijing (Yin et al. 2011). Urban
103 storm water is considered as one of the most detrimental hazards in Beijing and shows
104 strong correlation with the summertime rainstorm events (Jia et al. 2012; Zhang et al.
105 2013). Therefore, the knowledge of regional precipitation characteristics especially
106 that of the summertime rainstorm, has great implications for the mitigation of storm
107 water in Beijing. Li et al. (2008) analyzed the climatic characteristics of diurnal cycles
108 of summer precipitation in Beijing and identified two separate peaks in precipitation

109 amount and frequency, one in the late afternoon and the other in the early morning.
110 Also in Beijing, Yin et al. (2011) found that in summer, the precipitation peaks at
111 night over the plains but in the afternoon over the mountains. Although these findings
112 greatly enriched the knowledge of the precipitation characteristics at finer scales in
113 Beijing, it should be noted that they are derived based on hourly records collected
114 from less than 30 stations sparsely located in the Greater Beijing Region (GBR) over
115 an area of 16,410 km². As suggested by Villarini et al. (2008) and Hofstra et al. (2010),
116 the spatial sampling error tends to be larger as the temporal integration scale becomes
117 smaller. Therefore, the uncertainty associated with temporal characteristics of
118 precipitation retrieved from a low-density gauge network can be large, in particular
119 from networks over highly heterogeneous surfaces, such as the urban areas (Kursinski
120 and Zeng 2006; Gervais et al. 2014; Yang et al. 2013). Besides, the spatial variability
121 of precipitation, especially that of the summertime rainstorm, in the GBR has not yet
122 been thoroughly examined as far as we know.

123 Motivated by these ideas, we utilize a dense gauge network and a newly available
124 weather radar to investigate the spatiotemporal characteristics of precipitation in GBR
125 by addressing the three specific questions: (1) what is the temporal variability of GBR
126 precipitation at sub-daily scale, which is related to short-duration summer rainstorms,
127 (2) what is the spatial characteristics of precipitation on the meso-gamma scale (i.e. <
128 20 km), focusing on the localized summer rainstorm processes over the GBR, and (3)
129 what is the appropriate approach to monitor the GBR precipitation in the context of
130 these variability characterized at sub-daily and meso-gamma scales?

131 In this paper, we start by describing the data and methodology used for the analysis in
132 section 2. Then, we investigate the spatiotemporal characteristics of precipitation in
133 the GBR in section 3: with data from dense gauge network and weather radar, the
134 general spatial pattern is first revisited, while following two parts focus on
135 quantifying sub-daily temporal variations as well as localized spatial pattern of
136 summer rainstorms. Based on these quantitative analysis results, in section 4 we
137 further discuss the impacts of different observational scenarios on the final retrieved
138 characteristics of the diurnal cycle and the summer rainstorm for precipitation in the
139 GBR, prior to final concluding remarks given in section 5.

140

141 **2. Data and methodology**

142 In this study, we use hourly observations collected from a dense gauge network and a
143 weather radar that are both located in the GBR for the analysis of precipitation
144 characteristics. The gauge network consists of 118 tipping-bucket gauges (their
145 locations are shown in Figure 1) and has been continuously running since 2008 in the
146 charge of the Beijing Water Affairs Bureau. The dataset based on this gauge network
147 is comprised with hourly precipitation records from 2008 to 2012 and has been
148 subject to strict data quality control procedures (Yang et al. 2014). The Da Xing
149 weather radar (an S-band Doppler radar, and its location is denoted by the red triangle
150 in Figure 1) installed by China Meteorological Administration (CMA) is operated at
151 nine elevation angles ranging from 0.5° to 19.5° every 6 minutes with a maximum
152 range of 460 km. The range resolution for this radar is 1 km while the azimuth

153 resolution is 1 °, and the radar data consists of reflectivity observations from 2008 to
154 2010. In this study, the radar-based dataset is first resampled into 1 km gridded hourly
155 data for the following analysis. We note that in this study the radar-based dataset is
156 only used for the spatial pattern analysis rather than the quantitative estimation of
157 rainfall so that we adopt a simple but the most general reflectivity-rainfall relationship
158 ($Z = 300R^{1.4}$, Z for reflectivity and R for rainfall intensity). We apply this conversion
159 relationship to get a quantitative precipitation estimate (QPE) data using the
160 reflectivity measured at the third elevation angle (2.4°) by avoiding beam-blockage
161 and ground-clutter.

162 The general precipitation pattern in the GBR is first investigated based on the gauge
163 data via the five statistics given as follows: annual accumulated precipitation,
164 precipitation occurrence (the rainy hours divided by the total hours of the 5-yr period,
165 24×1827), hourly and daily maximum precipitation, and the exceedance probabilities
166 of precipitation at various time-scales (Ciach and Krajewski 2006). To illustrate the
167 spatial variations of the exceedance probability curves, rain gauges belonging to
168 different sub-regions with different statistical features of precipitation are selected to
169 calculate regional averaged results (as detailed in section 3.1).

170 The temporal characteristics analysis follows the methods by Zhuo et al. (2013) and
171 Li et al. (2014). For each hour of a day, precipitation amount (PA) is defined as the
172 accumulated precipitation amount for this hour averaged over the 1827 days of the
173 study period. With consideration of only rainy hours, precipitation intensity (PI) is
174 defined as the accumulated precipitation amount for this hour only divided by the

175 rainy days during the study period. In other words, PA is unconditional average of
176 mean rainfall amount for a particular hour while PI is a conditional average (on rainy
177 days). Precipitation frequency (PF) is calculated as rainy days divided by 1827 days
178 for the hour being considered. In fact, PF also equals to PA divided by PI. It should
179 also be noted that the local standard time (LST, i.e. Beijing Time as UTC +8 hours) is
180 used in this study.

181

182 **3. Spatiotemporal characteristics of precipitation**

183 **3.1 Spatial pattern**

184 Figure 2 shows the spatial pattern of precipitation in the GBR summarized by the
185 follow statistics “i.e. annual accumulated precipitation, precipitation occurrence,
186 hourly and daily maximum precipitation”. The average annual precipitation during
187 2008-2012 ranges from 202.4 mm to 719.6 mm as shown in Figure 2a. Relatively
188 large precipitation amount (larger than 500 mm) are mainly observed in the south
189 central and northeastern areas. As shown in Figure 2b, precipitation occurrence at
190 hourly scale ranges from 1.32% to 5.29%, and its spatial distribution resembles that of
191 the annual precipitation. Since urban floods are mainly caused by high-intensity
192 precipitation, we also examine the spatial patterns of maximum accumulated
193 precipitation at hourly and daily scales. The hourly maximum precipitation has a
194 similar spatial distribution as the annual precipitation, of which high values appear in
195 the south central and northwestern areas (Figure 2c). However, the high values of
196 maximum daily precipitation are only observed in south central region (Figure 2d). It

197 can thus be inferred that heavy local floods may most likely occur in the south central
198 part of the GBR. Collectively, the results shown in Figure 2 suggest that, precipitation
199 events with high intensity and frequency are mainly concentrated in the south central
200 and northeastern parts of the GBR, leading to the large precipitation amount in the
201 two regions.

202 To further investigate the spatial distribution of precipitation over the whole GBR, we
203 conduct a Kriging interpolation of annual precipitation amount observed at the 118
204 gauges. Based on the interpolation results, we have identified three typical regions, of
205 which two regions (labeled as A and B in Figure 3) experience annual precipitation
206 amounts larger than 560 mm (the 75% percentile of mean annual precipitation for the
207 whole GBR) whereas the third region (labeled as C in Figure 3) holds an amount less
208 than 420 mm (the 25% percentile of mean annual precipitation). We note that,
209 according to the land use classification of the GBR (not shown here), region A is
210 categorized as urban and built-up area. It is also noteworthy that both region A and B
211 identified by the interpolation result generally overlap with the typical precipitation
212 regions found by Yang et al. (2013) via meso-scale WRF simulations: the
213 precipitation regime tends to concentrate in the climatologically downwind region of
214 the urban and built-up area (i.e. region B in this study). In addition, region C is
215 located in the northwestern mountainous area of the GBR, where the gauges are
216 generally located in the interior valleys of mountains.

217 Based on this region classification scheme, the region-dependent characteristics of
218 precipitation are further examined in terms of the exceedance probability at the hourly

219 and daily scales in Figure 4a and 4b, respectively. Among the sub-regions, region C
220 has the lowest exceedance probability given the same precipitation rate, whereas at
221 hourly scale, region A and region B demonstrate similar patterns of exceedance
222 probability when rain rate less than 30 mm/h, while the exceedance probability of
223 region A is remarkably higher than the others when rain rate higher than 30 mm/h
224 (Figure 4a). At daily scale, patterns in region A and region B are similar for all the
225 rain rate (Figure 4b). This analysis of exceedance probabilities demonstrates
226 consistent results as previous studies of precipitation in the GBR: the urban and
227 built-up areas experience more high intensity precipitation events than their
228 surrounding areas (Guo et al. 2006; Yang et al. 2014).

229 Based on the above results, we also find that the precipitation regime demonstrates
230 significant spatial variability over the GBR. Although exploring the thorough
231 rationale is beyond the scope of this study, the variability can be linked to previous
232 data- and model-driven studies of precipitation regime over urban area by discussing
233 the following aspects. First, precipitation events with higher amount and intensity are
234 more frequently observed in upslope side of the mountain compared with the
235 surrounding regions due to the effects of topography induced local circulation (Clark
236 and Slater 2006; Daly et al. 1994; Li et al. 2014). Yin et al. (2011) confirmed this
237 effect in the GBR by examining the mountain-valley circulation patterns. This finding
238 agrees with our results that higher precipitation is observed along the boundaries
239 between the plain and mountainous area (region B in Figure 3) and less rainfall is
240 observed in the interior mountainous area (region C in Figure 3). In addition to the

241 effects caused by mountains, cities can modulate the precipitation regime mainly by
242 three mechanisms, including urban heat island effects (Dixon et al. 2003; Oke, 1982),
243 urban canopy effects (Chen et al. 2011; Miao et al. 2011) and urban aerosol effects
244 (Jin et al. 2005; Ntelekos et al. 2009). These urban effects lead to the more
245 precipitation concentrated in the cities and their climatologically downwind areas
246 (Davies et al. 2013). Yang et al. (2013) and Yang et al. (2014) investigated the impact
247 of urbanization on heavy precipitation by WRF simulations, suggesting that the
248 large-scale precipitation patterns are insensitive to the local-scale urban forcings, but
249 the existence of cities does facilitate the formation of convergence zone and provides
250 favorable conditions for deep convection over cities. This simulation-based results
251 show consistency with our observational study that the precipitation events with
252 larger rainfall and higher intensity are more observed in urbanized areas (region A in
253 Figure 3). Overall, the complex precipitation regime over the GBR is shaped by a
254 combination of meso-scale and synoptic scale systems, the regional mountain-valley
255 circulation induced by the topography and possibly urban effects caused by
256 urbanization.

257 **3.2 Diurnal cycles**

258 In this section, we investigate the annual averaged diurnal cycles of PA, PI and PF
259 over the GBR from 2008 to 2012. As shown in Figure 5a, PA peaks at 21 LST and
260 then decreases until noon. Compared with PA, two peaks can be observed in the
261 diurnal cycle of PI: the higher peak occurs around 17 LST and the lower one appears
262 at around 02 LST. The difference between diurnal cycles of PA and PI implies the

263 temporal distribution of high intensity rainfall and other rainfall events are different.
264 The dual-peak pattern is also found in the diurnal cycle of PF, where the higher peak
265 occurs during 20-24 LST whereas the lower one appears during 12-16 LST. The
266 above results indicate that precipitation events in the GBR occur mainly between the
267 afternoon and the early night. It is also shown that precipitation intensity is relatively
268 lower in the afternoon than in the nighttime.

269 To further investigate the region-dependent features of diurnal cycles, we categorize
270 the gauges according to their sub-region categories so as to obtain sub-regional
271 averaged diurnal cycles, and the diurnal variations of PA, PI, and PF for each
272 sub-region are shown in Figure 6. The diurnal cycles of PA in regions A and B
273 demonstrate similar patterns with an evening peak (during 18-21 LST) as well as a
274 nighttime peak (during 00-03 LST). However, in region C, the only peak of PA is
275 much smaller and shifts to ~16 LST. As for PI, it is evident that there is an afternoon
276 peak for all the three regions, while another early nighttime peak around 00-03 LST
277 can only be observed in regions A and B. The most significant difference between the
278 urban and built-up areas (i.e. region A) and the mountainous areas (i.e. region C) is
279 observed in the evening and in early nighttime, when the urban heat island effect is
280 recognized as the strongest during a day (Arnfield, 2003). Therefore, it potentially
281 reflects the alternation of local thermal circulation by urban heat island effects, we
282 suspect.

283 Compared to PA and PI, no significant peak can be observed for PF, and there is no
284 apparent consistence in the occurrence time of the PF peak over different regions. In

285 region A, there is only one weak peak (approximately 3%) occurred in the early
286 nighttime. However, region B presents a pattern with two weak peaks: one is similar
287 to region A's nighttime peak and the other occurs in the afternoon, which is possibly
288 caused by local convective precipitation. By contrast, region C also has an afternoon
289 weak peak (about 2.7%). All these regimes reflect that the complexity of precipitation
290 system over GBR, which is not only dominated by meso-scale and synoptic scale
291 systems but also influenced by localized controlling factors (orographic effect, urban
292 heat island, etc.).

293 It has been reported that precipitation over the contiguous China has large diurnal
294 variations with considerable regional features. The northeast (40°–50°N, 110°–130°E)
295 China has late afternoon PA maxima (15-18 LST), which can be explained by surface
296 solar heating with concomitant maximum low-level atmospheric instability and moist
297 convection in the afternoon (Yu et al. 2007). Although the GBR is situated in the
298 northeast China, its regional diurnal variation of precipitation, as discussed above,
299 distinguishes from the national large-scale pattern. It is suspected that local effects
300 mentioned above (i.e. orographic effect, the urban heat island effect) will accelerate
301 the evening convection, and because the evening and early nighttime PA peaks in part
302 of the GBR, suggesting the GBR potentially has its distinctive diurnal cycles modified
303 by local circulations processes.

304 Our estimated diurnal cycles are also inconsistent with previous results by Yin et al.
305 (2009) and Yin et al. (2011). Yin et al. (2009) suggested that diurnal patterns of PF
306 and PA were quite similar over the whole north China, except that the afternoon

307 maximum of PA was relatively higher. Therefore, Yin et al. (2011) applies the result
308 of Yin et al. (2009) directly to the GBR since the city belongs to north China.
309 However, according to our study, there are obvious differences between the pattern of
310 PA and PF in GBR. Since PA equals to PI multiplied by PF. The differences between
311 the pattern of PA and PF is attribute to the diurnal variation of PI. Compared with the
312 whole north China, local effects may be more significant in the GBR so that there is a
313 peak of PI occurs at night. This new finding indicates that a caution should be paid
314 when we apply the general conclusion drawn over a large region to a small area,
315 especially those are regions with relatively complex topography and land-use.

316 By conducting an interpolation of gauge-based statistics via the Kriging method, we
317 further investigate the spatial patterns of hourly peaks of PA, PF and PI (denoted as
318 PPA, PPI and PPF, respectively) over the whole GBR. The spatial pattern of PPA is
319 shown in Figure 7a, where large PPA values appear in the northeast and south central
320 regions of GBR while small ones concentrate in the western mountainous area. The
321 largest value 0.15 mm of PPA is observed in the northeastern downwind region of the
322 GBR urban core, where the storm cells tend to merge as found by Yang et al. (2014).
323 Compared to the spatial pattern of PPA, the larger values of PPI mainly appear in
324 southeastern, northeastern and part of southwestern region whereas the smaller ones
325 are found in the northwestern mountainous area (Figure 7b). The different spatial
326 pattern of PPA and PPI suggests heavy rainfall does not always occur in places where
327 there is large total rainfall. As shown in Figure 7c, PPF holds a different spatial
328 pattern compared to PPA and PPI. The high values of PPF are observed in part of

329 southern region, indicating that this region experiences more precipitation events than
330 other parts during the same hours. The polygon pattern of PPF may be attributed to
331 the high variability across the neighboring stations, which in turn implies high
332 resolution measurements are mandatory to resolve the spatial characteristics of
333 precipitation in GBR.

334 The occurrence time of PPA, PPI and PPF are also presented in Figure 7a, 7b and 7c,
335 respectively, in a clock-style annotation with arrowhead pointing to the time. As is
336 shown in Figure 7a, PPA in the northeastern and south central regions occurs in the
337 evening (18-23 LST) or midnight (02-03 LST), whereas in the northwestern
338 mountainous region it occurs in the afternoon (15-18 LST). Similar as PPA, PPI
339 (shown in Figure 7b) in northeastern and south central regions occurs in the evening
340 (18-23 LST). However, the emerging time of PPI in the northwestern mountainous
341 region does not demonstrate a clear pattern. As for PPF, its occurrence time in
342 different regions presents a diverse pattern and thus cannot be generalized in a
343 straightforward way.

344 **3.3 Characteristics of summer rainstorm**

345 Due to the particular importance of summer rainstorm in the GBR, we also examine
346 the characteristics of summer rainstorm in this section. The storm events are first
347 identified with the rain gauge observations as those events with average precipitation
348 of GBR above 20 mm. Thanks to the broad coverage and high spatiotemporal
349 resolution of weather radar, the investigation of the summer rainstorm characteristics
350 is conducted with the estimated precipitation information based on radar observations

351 (details refer to Section 2). It is noted that the observations from the gauge network
352 are not used in the subsequent analysis, due to its limited ability to represent the
353 spatial pattern of precipitation compared with the high resolution data provided by
354 weather radar.

355 Following the radar-based storm-scale analysis method given by Li et al. (2014), the
356 rainstorm cells are identified and quantified by the following three steps:

- 357 1) Rainstorm pixel identification: The rainstorm pixels are determined as those with
358 precipitation intensity larger than the threshold R_T (10 mm h^{-1} in this study, or ~ 39
359 dBZ in reflectivity, suggested by China Meteorological Administration, 2012);
- 360 2) Rainstorm cell segmentation: the determined rainstorm pixels are clustered by
361 minimizing their distance variance with the isolated ones excluded.
- 362 3) Shape approximation: As rainstorm cells can be approximated with an elliptical
363 shape by TITAN algorithm (Dixon and Wiener 1993), all the segmented rainstorm
364 cells are thus approximated with ellipses and the major and minor radii (denoted
365 by R_{major} and R_{minor}) as well as the coverage area (denoted by A_R) can be estimated
366 for subsequent analysis.

367 With the above 3-step procedure, 721 rainstorm cells are identified for all the 34
368 rainstorm events during the 2008 to 2010 (Table 1). The life cycle (denoted by t_R) of
369 the rainstorm is 11.4 h on average. The storm coverage area A_R ranges from 25 to
370 958.8 km^2 , whereas the major (minor) radius R_{major} (R_{minor}) of estimated ellipses varies
371 within 4.31–20.58 km (1.85–9.10 km). The averaged aspect ratio (R_{major}/R_{minor}) is 2.5,
372 implying the rainstorms cells in the GBR feature long and narrow shapes. It is noted

373 that the smaller rainstorm cells ($A_R < 100 \text{ km}^2$) demonstrate narrower shapes than the
374 larger ones.

375 The intra-event variability of rainstorms which contains more than 10 cells in
376 coverage area and axis length is shown in Figure 8a and 8b, respectively. Significant
377 variability is observed according to both the coverage area (Figure 8a) and axis length
378 (Figure 8b) among most rainstorm events, indicating the complexity in the rainstorm
379 characteristics in the GBR. For instance, the rainstorm cells of the event on July 23,
380 2009 (the date is highlighted in Figure 8) demonstrate high intra-event variability of
381 the coverage areas (varying from 44 to 13288 km^2) and the axis length (ranging
382 within 3.6–130.5 and 1.6–50.2 km for the major and minor radius, respectively). As
383 discussed above, the intra-event variability, accompanying the inter-event variability
384 discussed above, to some extent demonstrates the challenges in monitoring
385 summertime local rainstorms in the GBR.

386 The spatial distribution of rainstorms is further examined by the rainstorm cell centers
387 (Figure 9). It is clear that most rainstorm cells are centered in the south central and
388 northeastern parts of the GBR, which is consistent with the spatial pattern of annual
389 rainfall derived from the gauge data (Figure 2). The rainstorm cells are further
390 classified by their cell average intensity (CAI). The five heaviest rainstorm cells ($30 <$
391 $\text{CAI} < 40 \text{ mm h}^{-1}$ and $\text{CAI} > 40 \text{ mm h}^{-1}$ denoted by orange and red dots in Figure 9,
392 respectively) are centered either on the boundary between the plains and mountains or
393 in the interior mountainous areas, implying the important role of the mountain-valley
394 topography in the formation of severe rainstorms in the GBR (Buytaert et al. 2006,

395 Daly et al. 1994).

396 **4. Appropriate observational scenarios for GBR precipitation monitoring**

397 Since the above results are obtained based on a dense gauge network (118 sites over
398 the GBR) and a weather radar, it is of great interest to know the dependence of such
399 results on the instrumentation. Therefore, in this section, the importance of gauge
400 density and weather radar is assessed by examining the consistency in the observed
401 spatiotemporal variability of precipitation under different instrumentation scenarios
402 over the GBR.

403 For the temporal variability, it is found the spatial sampling scale has significant
404 impacts on the captured temporal characteristics of precipitation, in particular on the
405 small temporal scales (Villarini et al. 2008, Hofstra et al. 2010). Assuming only
406 limited gauges are available for an analysis as implemented in this study, will those
407 temporal characteristics obtained above still hold? In other words, what is the
408 mandatory minimum gauge density for the GBR to capture the characteristics of
409 diurnal cycles of precipitation adequately? In section 3.2, we have learned that rainfall
410 characteristics distinguishes between the mountainous and plain regions, suggesting
411 the representativeness of gauge density for the two regions should be examined
412 separately. As such, we choose only the plain area (elevation less than 150 m) as a test
413 bed to conduct a sensitivity analysis under different gauge density scenarios with the
414 spatially averaged PA, PI and PF as the indicators.

415 Setting the density with complete gauges in plain area as the benchmark scenario (i.e.
416 55 sites in total) with density ratio (r_p hereinafter) of 1, ten gauge density ratios

417 (provided in Table 2) are designed. To minimize the possible spatial sampling errors,
 418 for a given density ratio r_p , we implement 100 realizations of the random sampling
 419 procedure and take the spatially averaged PA, PI and PF obtained by full gauges with
 420 $r_p = 1$ as the benchmark. To quantitatively examine the impact of gauge density on the
 421 diurnal cycles estimation in plain area, the hourly mean bias B_I and the correlation
 422 coefficient CC between the estimated and the benchmark values of a specific indicator
 423 I (one of PA, PI and PF) and their corresponding incremental difference δ under a
 424 given r_p are calculated as follows:

$$B_I = \frac{1}{24} \sum_{h=1}^{24} \frac{|I_e(h) - I_r(h)|}{I_r(h)} \quad (0)$$

$$CC_I = \frac{\text{Cov}(I_e, I_r)}{\sigma_{I_e} \sigma_{I_r}} \quad (0)$$

$$\delta_B = \left| \frac{\Delta B_{r_p}}{\Delta r_p} \right| \quad (0)$$

$$\delta_{CC} = \left| \frac{\Delta CC_{r_p}}{\Delta r_p} \right| \quad (1)$$

425 where h denotes the hour of a day, $\text{Cov}(a,b)$ the covariance function of a and b , σ
 426 the standard deviation and Δ the difference operator. The subscripts e and r indicate
 427 the estimate and the benchmark, respectively.

428 Figure 10 shows the hourly mean bias and its corresponding incremental difference of
 429 PA, PI and PF with different gauge densities. The bias decreases as the gauge density
 430 ratio increases and approaches as low as 5% at $r_p = 0.5$. It is noteworthy that as r_p is
 431 larger than 0.6, the incremental difference values of PA, PI and PF are less than 0.1,
 432 implying that the marginal improvement by increasing gauge density becomes limited.

433 Similar implication is also obtained for the correlation coefficients of PA, PI and PF
434 and their corresponding incremental differences as shown in Figure 11: very little
435 marginal benefits can be obtained when r_p becomes larger than 0.6. As such, we
436 identify 0.6 as the representative gauge density ratio (correspond to 30 gauges and a
437 representative area of 239.5 km² per gauge), with which the characteristics of diurnal
438 cycles of precipitation in the plain area of GBR can be adequately captured.

439 However, given a gauge density ratio of 0.6, it can be insufficient to capture the
440 spatial variability of rainstorms under certain scenarios in the GBR, since the
441 coverage area of rainstorm cells ranges from 25 to 958.8 km² with a median value of
442 ~163 km², which is much smaller than the representative area per gauge of such a
443 gauge network (i.e. 239.5 km²). In other words, the geometric features of some
444 rainstorms can hardly be resolved by a gauge network that satisfies the criteria for
445 capturing temporal variability of precipitation in the GBR. Even under the present-day
446 gauge density, a gauge network still has difficulty in capturing all the local rainstorms
447 that can be resolved by a weather radar. As such, in order to capture the finer spatial
448 variability of precipitation in the GBR, it is necessary to increase the gauge density or
449 to install weather radars. However, on one hand, the refinement of a gauge network is
450 not only costly and but also infeasible under certain conditions (e.g. installment of
451 gauges in densely urbanized area such as central business districts); on the other hand,
452 the remarkable inaccuracy in current radar-based quantitative precipitation estimate
453 (QPE) systems raise high uncertainty in the assessment of quantity-sensitive
454 characteristics of precipitation (such as PA and PI). Therefore, it is recommended that

455 the optimal strategy for GBR is to jointly utilize different instruments and to
456 synthesize multiple data sources, rather than to adopt a “one-solution-fits-all”
457 strategy.

458 **5. Concluding remarks**

459 In this study, we investigated the spatiotemporal characteristics of precipitation over
460 the Greater Beijing Region by using a five-year dataset of hourly precipitation
461 collected from a dense gauge network consisting of 118 sites and a three-year dataset
462 of hourly precipitation estimates obtained by an S-band Doppler radar. In addition, we
463 further discussed the impact of gauge density and weather radar on capturing
464 spatiotemporal variability of precipitation in GBR. The major findings are
465 summarized as follows:

466 1. High spatial variability is observed for precipitation regimes over the GBR as
467 indicated by the selected statistics, including annual accumulated precipitation,
468 precipitation occurrence, hourly and daily maximum precipitation. Large
469 precipitation amount and high intensity are mainly found in the south central and
470 northeastern parts of the GBR, whereas the high values of daily maximum
471 precipitation only appear in the south central part. It is also worth noting that the
472 hourly and daily precipitation amounts in northwestern mountainous area are
473 significantly lower than other parts of the GBR. Besides, analysis of exceedance
474 probabilities at hourly scale reveals that southern urban area experiences more
475 heavy precipitation events compared to its surrounding areas.

476 2. Three sub-regions can be identified by the gauge-based annual precipitation:

477 regions A and B have annual precipitation more than 560mm (the 75% percentile
478 of mean annual precipitation in GBR), while region C holds annual precipitation
479 less than 420mm (the 25% percentile of mean annual precipitation in the GBR).
480 Since region A features for its built-up urban surfaces while region C is
481 categorized as the mountainous area, this region-dependent precipitation regime
482 can be explained by the regional mountain-valley circulation induced by the
483 topography combined with the possible effects by urbanization.

484 3. The diurnal cycle of PA (precipitation amount) peaks in the evening and decreases
485 till noon, while that of PI and PF presents a dual-peak pattern. PI (precipitation
486 intensity) and PF (precipitation frequency) both have two peaks: the stronger ones
487 of PI and PF both occur in the evening while the weaker ones appear in the early
488 nighttime for PI and in the afternoon for PF, respectively. Remarkable spatial
489 variability also exists in the diurnal cycles over the GBR. For PA and PI, the
490 diurnal cycles of regions A and B peak in the evening (18-21 LST), whereas that
491 of region C peaks in the afternoon (15-18 LST). As for PF, its peak appears later
492 in region C than in regions A and B.

493 4. Rainstorms in the GBR are characterized by short durations (average ~11.4 hours)
494 and highly localized patterns (R_{major} and R_{minor} vary within 4.31–20.58 km and
495 1.85–9.10 km, respectively) based on the newly available radar data. The
496 extracted storm centers show that most rainstorms are located in the south central
497 and northeastern part of the GBR. Given the current gauge density in the GBR
498 with the representative coverage area of 136 km² per gauge, some of the localized

499 rainstorms of the GBR cannot be resolved by the gauge network with the
500 present-day density.

501 5. The observed spatiotemporal variability is shown to be affected by various
502 instrumentation scenarios. By varying the gauge density ratio, it is found that a
503 gauge density ratio of 0.6 (corresponding a representative area of 239.5 km² per
504 gauge) can adequately capture the characteristics of diurnal cycles using different
505 summary statistics (i.e. PA, PI and PF) in the plain area of GBR. However, even
506 given such a gauge density ratio, the gauge network may be unable to resolve the
507 finer spatial variability associated with the summer rainstorms. Therefore, it is
508 suggested to jointly utilize different instruments (e.g. gauge network, weather
509 radar, etc.) and to synthesize multiple data sources (e.g. ground rainfall records,
510 radar measurements, etc.) in future so as to better monitor and characterize the
511 spatiotemporal variability of precipitation in the GBR.

512

513 **Acknowledgement**

514 This work is supported by the National Science Foundation of China under Grant No.
515 51190092 and 51409147, by China Postdoctoral Science Foundation under Grant No.
516 2015T80093 and by the Ministry of Science and Technology of China under Grant
517 No. 2013DFG72270. We are grateful to the Beijing Water Affairs Bureau and China
518 Meteorological Administration for the assistance in providing data.

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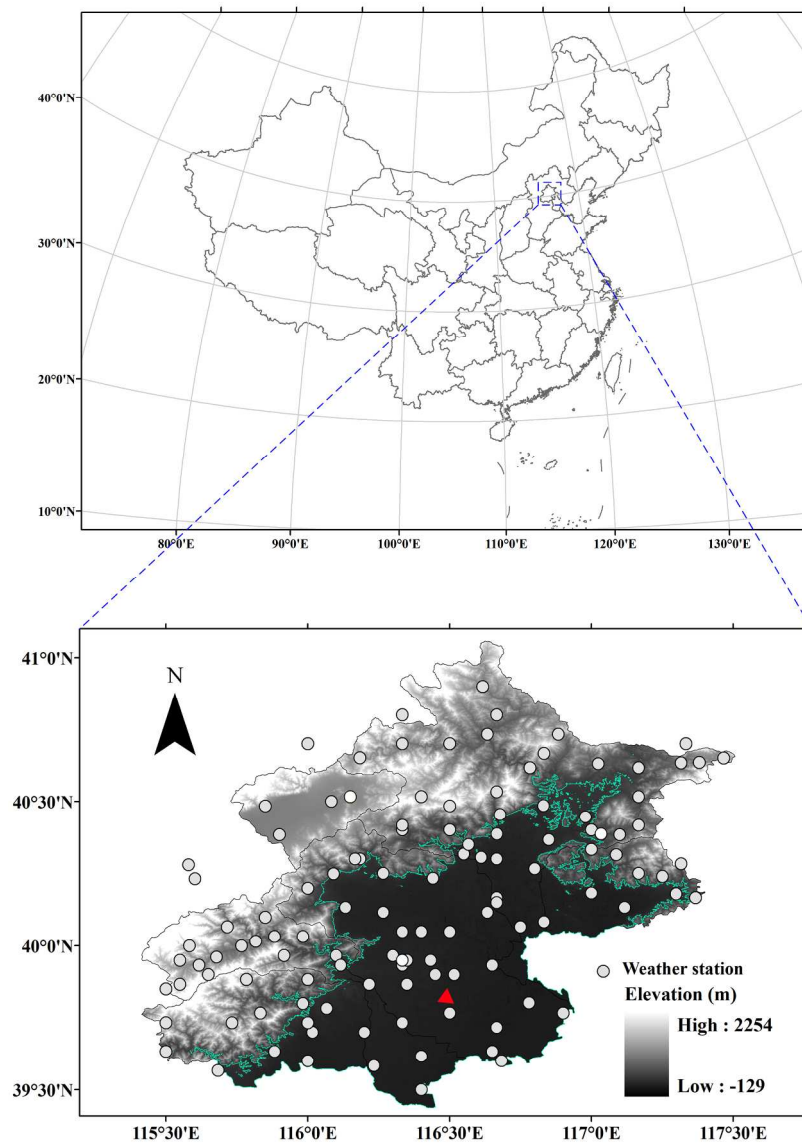


Figure 1 The topography in GBR. Gray dots and the red triangle indicate 118 rain-gauge sites and the S-band Doppler radar, respectively.
200x287mm (300 x 300 DPI)

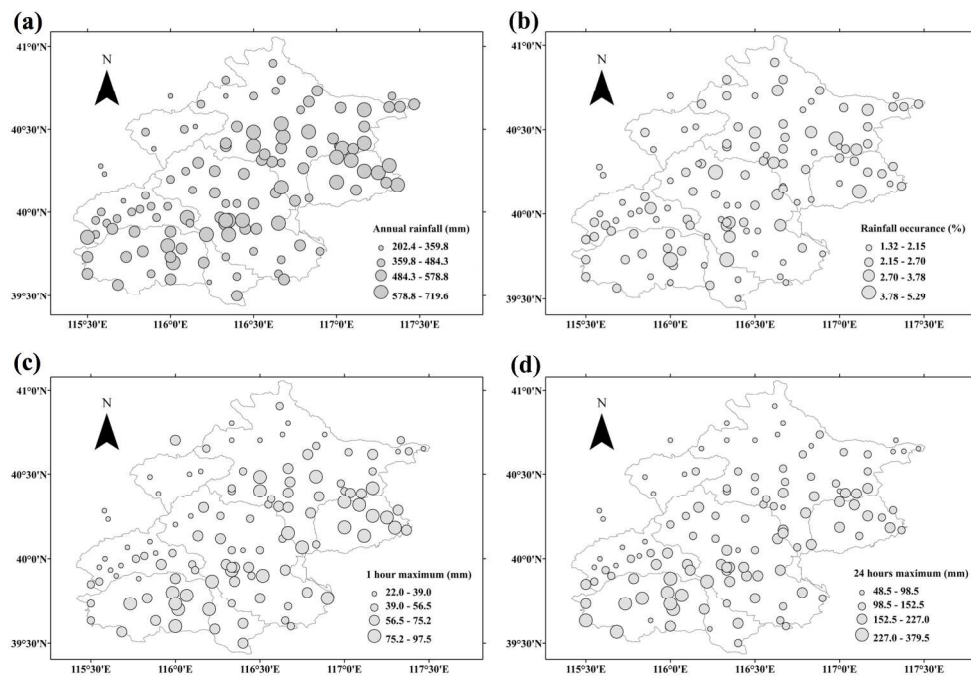


Figure 2 Spatial pattern of precipitation during 2008-2012 in GBR of (a) annual accumulated precipitation (mm), (b) precipitation occurrence (%), (c) 1-hour maximum precipitation (mm) and (d) 24-hour maximum precipitation (mm).
253x179mm (300 x 300 DPI)

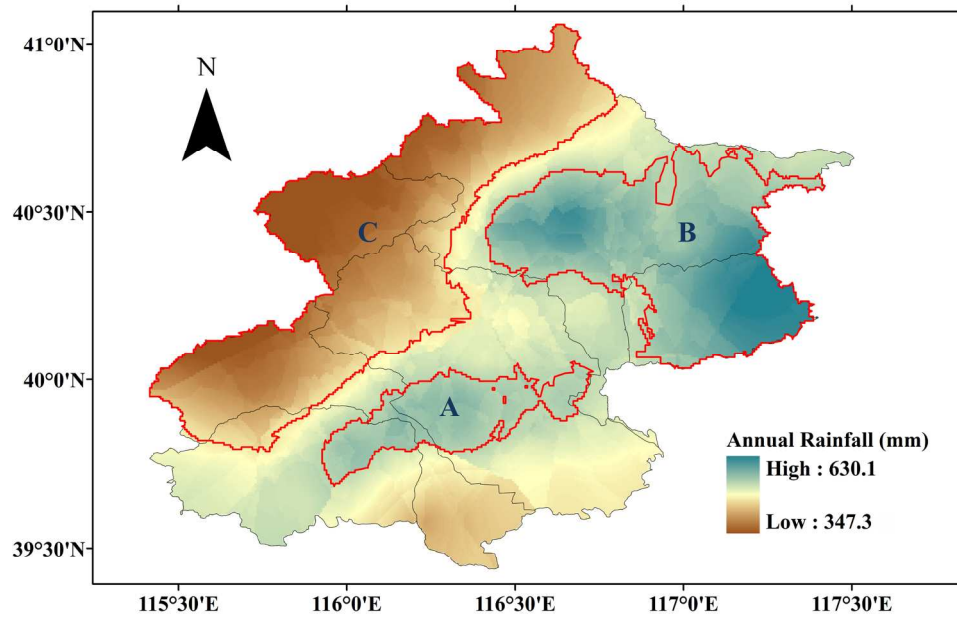


Figure 3 Spatial distributions of annual precipitation and three identified sub-regions.
296x210mm (300 x 300 DPI)

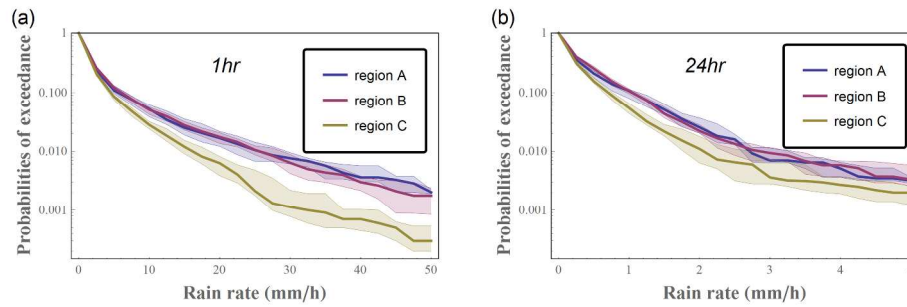


Figure 4 Sub-regional probabilities of exceedance for rain rate within (a) 1-hour and (b) 24-hour during 2008-2012 in GBR, the thick line represents the median value of each sub-region, while the thin line are the lower 25th and upper 75th quartile.
282x86mm (300 x 300 DPI)

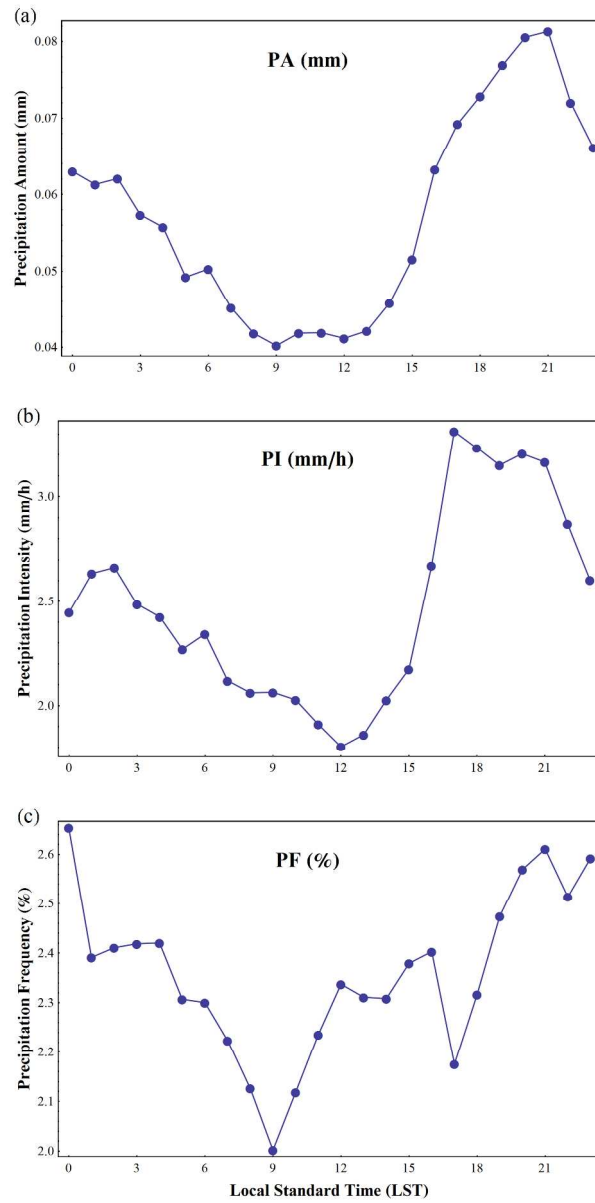


Figure 5 Regional averaged diurnal cycle of (a) PA (mm), (b) PI (mm hr⁻¹) and (c) PF (%) in GBR. 176x327mm (300 x 300 DPI)

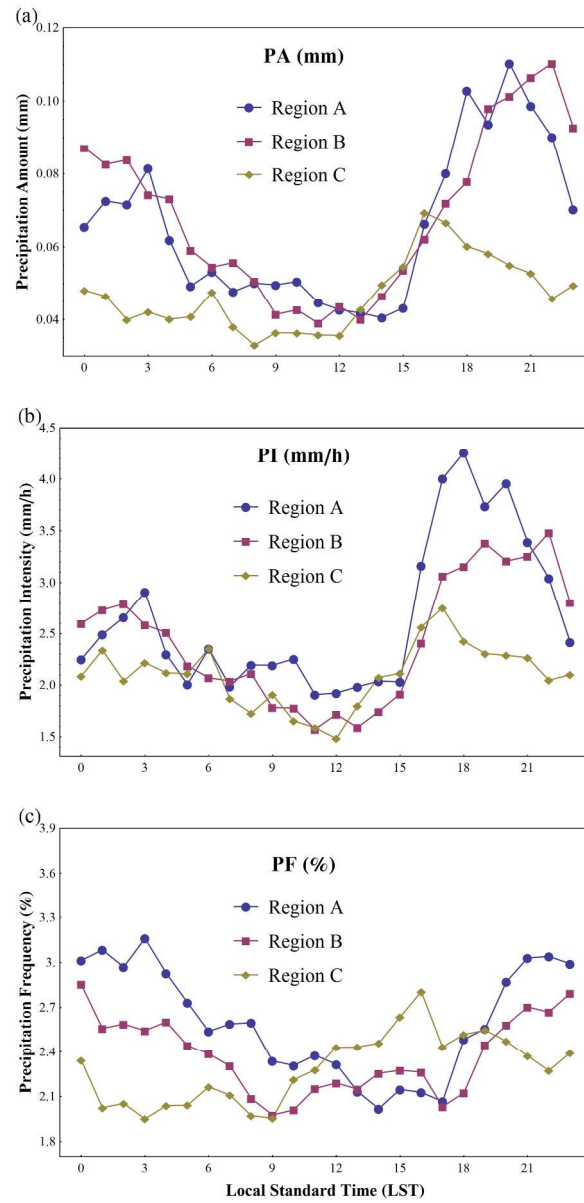


Figure 6 Sub-regional averaged diurnal cycle of (a) PA (mm), (b) PI (mm hr⁻¹) and (c) PF (%) in GBR. 176x327mm (300 x 300 DPI)

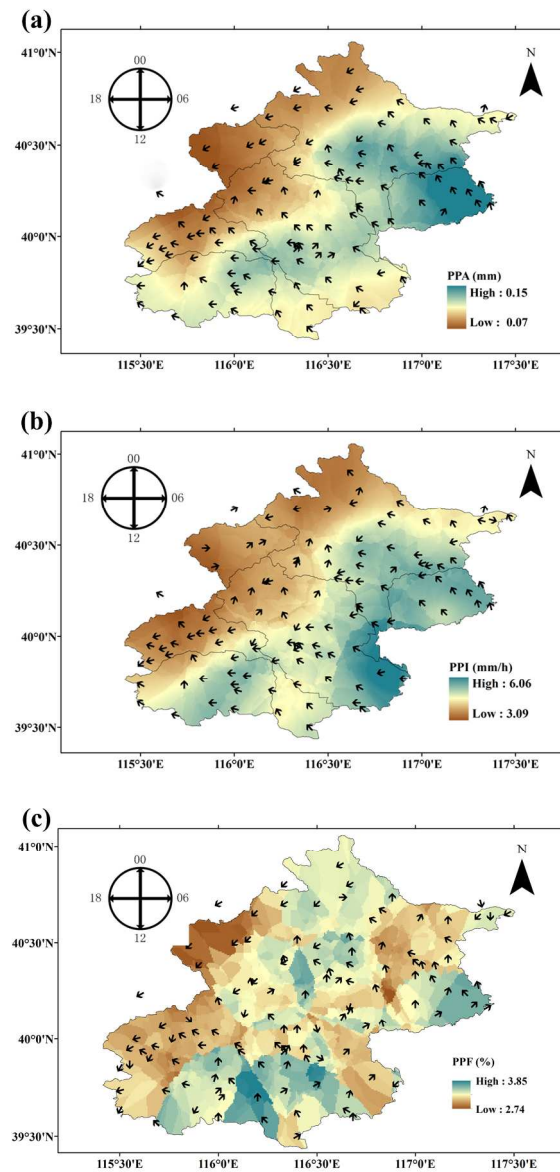


Figure 7 Spatial distributions of (a) PPA (mm), (b) PPI (mm hr-1), (c) PPF (%) (The background colors indicate the magnitude of PPA, PPI and PPF values and the arrow pointer on a circular clock dial indicates the peak time).
138x287mm (300 x 300 DPI)

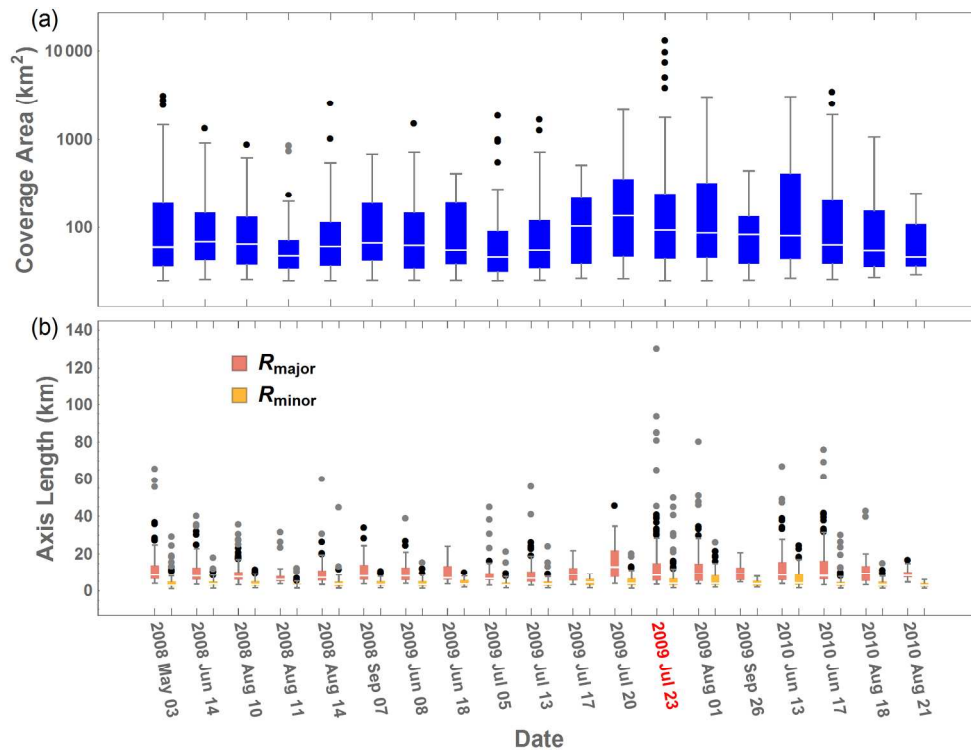


Figure 8 Boxplot of estimated rainstorm features: storm areas (top) and storm radii (bottom), during 19 typical storm events which each contains more than 10 storm cells (The circle represents the outlier values. Each box ranges from the lower 25th quartile to the upper 75th quartile. The median value is denoted by the middle line in the box.).
211x159mm (300 x 300 DPI)

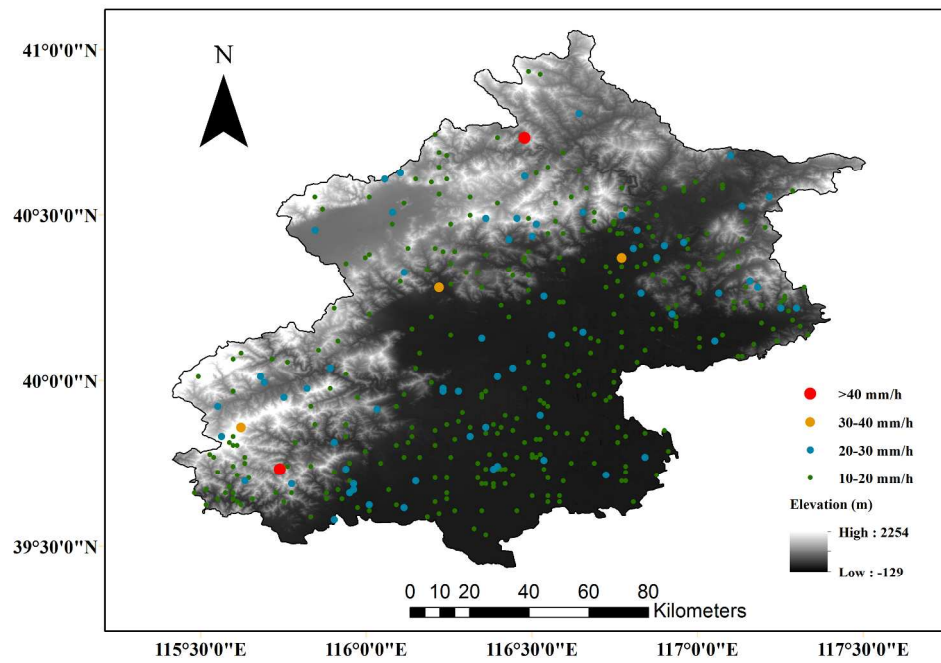


Figure 9 Storm cells locations identified by radar precipitation data from 2008 to 2010.
297x210mm (300 x 300 DPI)

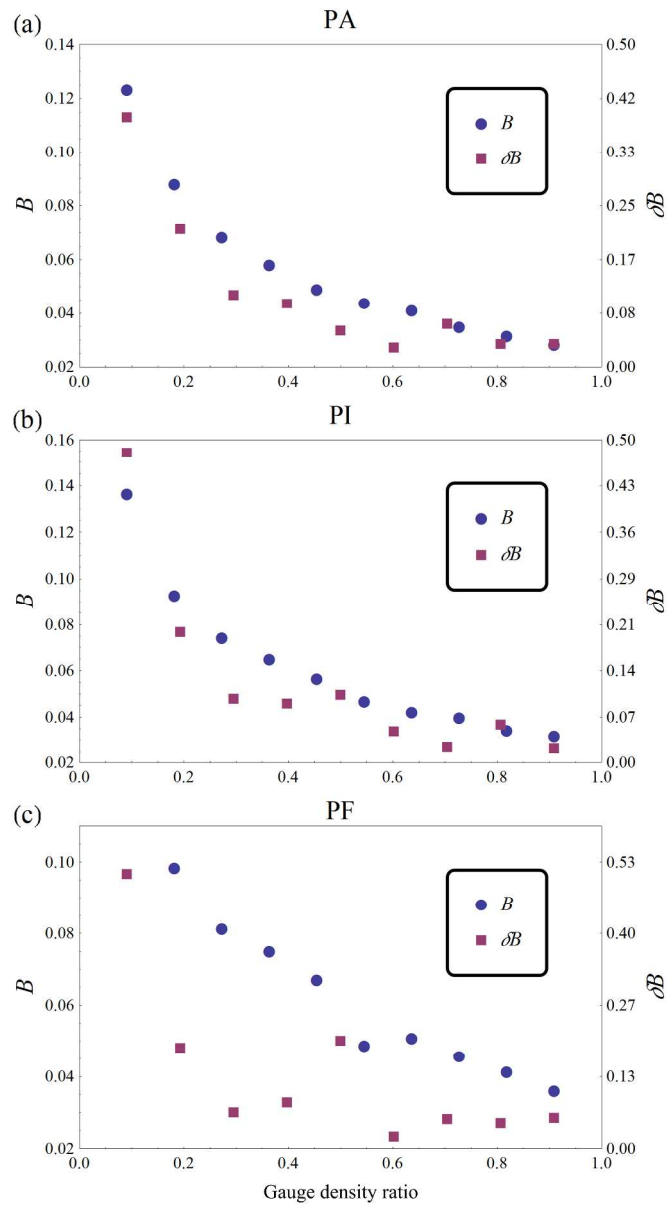


Figure 10 The bias and its corresponding incremental difference of (a) PA, (b) PI and (c) PF with different gauge density ratios.
256x467mm (300 x 300 DPI)

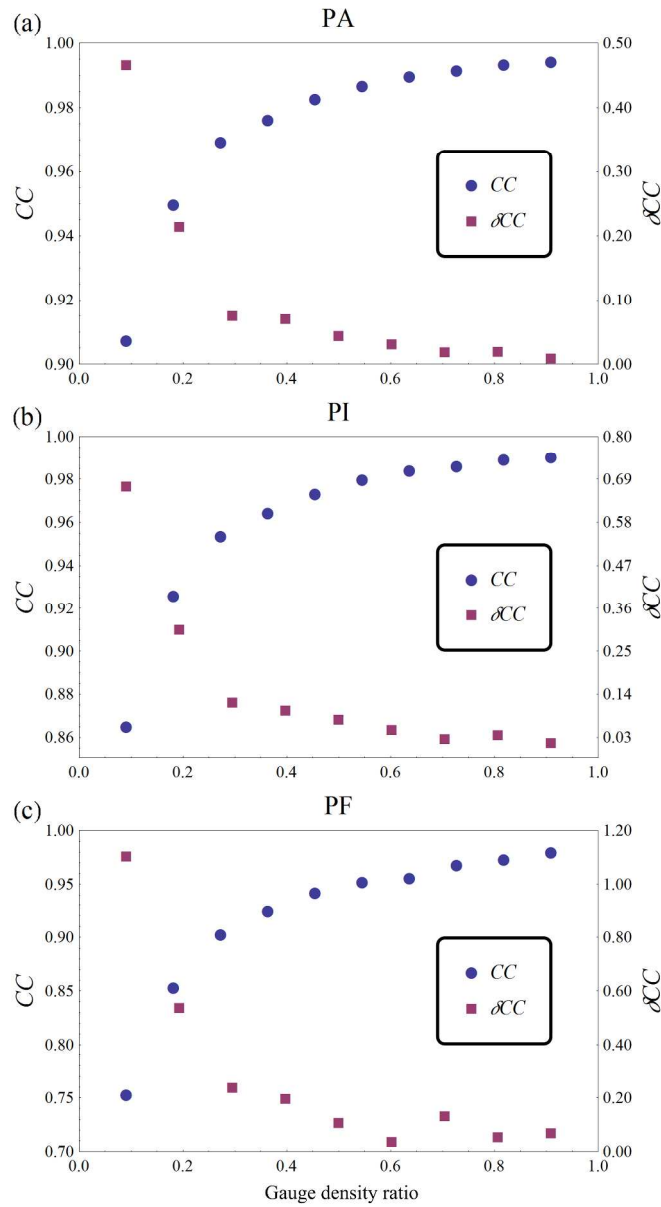


Figure 11 The variations in correlation coefficient and its corresponding incremental difference of (a) PA, (b) PI and (c) PF with different density ratios.
257x471mm (300 x 300 DPI)

Tables:

Tables 1 Summary of storm events during 2008-2010 in the GBR. The storm events were identified with the rain gauge observations as those events with average precipitation of GBR above 20 mm (* denotes the events without identified rainstorms, and # denotes the event where radar data is missing. R_{major} , R_{minor} and Area are given in their mean values.)

Date	Duration (h)	Number of storm cells	R_{major} (km)	R_{minor} (km)	Area (km ²)
2008/5/3	10	53	14.97	5.80	330.91
2008/5/11	1	1	4.31	1.85	25.00
2008/6/14	26	53	12.48	4.98	201.29
2008/7/4*			—		
2008/7/15	6	4	8.91	2.39	56.16
2008/7/31#			—		
2008/8/10	24	92	9.35	4.18	110.05
2008/8/11	19	31	8.37	3.81	114.88
2008/8/14	11	53	9.77	4.77	151.99
2008/9/7	12	45	11.92	4.54	162.32
2008/9/9*			—		
2008/9/21	4	4	6.99	1.85	35.72
2009/4/23*			—		
2009/6/8	15	34	9.21	3.76	97.28
2009/6/18	7	7	8.77	3.12	62.95
2009/7/5	15	46	10.17	4.47	165.13
2009/7/13	9	50	10.59	4.84	167.75
2009/7/17	15	28	10.94	5.24	164.75
2009/7/20	18	50	16.76	5.75	317.37
2009/7/23	16	34	20.58	8.77	958.83

2009/8/1	12	35	17.50	8.03	508.46
2009/8/19	3	5	13.22	4.20	199.88
2009/9/26	7	2	7.43	3.03	54.19
2010/5/18*			—		
2010/6/13	10	23	19.57	9.10	693.76
2010/6/17	16	41	18.62	6.73	442.64
2010/7/9*			—		
2010/7/11*			—		
2010/8/4	5	5	9.56	2.84	66.00
2010/8/18	12	18	11.63	5.07	186.72
2010/8/21	9	3	8.36	2.80	50.83
2010/9/16*			—		
2010/9/18*			—		
2010/9/21	4	4	6.99	1.85	35.72

Table 2 Summary of network characteristics of different gauge density ratios

Gauge density ratio	Number of gauges	Representative area per gauge (km ²)	Incremental difference per gauge (km ²)
0.1	5	1437	--
0.2	10	718.5	718.5
0.3	15	479	239.5
0.4	20	359.3	119.7
0.5	25	287.4	71.9
0.6	30	239.5	47.9
0.7	35	205.3	34.2
0.8	40	179.6	25.7
0.9	45	159.7	19.9
0.99	50	143.7	16