Diurnal Variations of Rainfall in Surface and Satellite Observations at the Monsoon Coast (South China)

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ABSTRACT

The complex features of rainfall diurnal cycles at the south China coast are examined using hourly rain gauge data and satellite products (CMORPH and TRMM 3B42) during 1998–2014. It is shown that morning rainfall is pronounced near the coasts and windward mountains, with high rainfall in the summer monsoon season, while afternoon rainfall is dominant on land, and nocturnal rainfall occurs at northern inland sites. Both satellite products report less morning rainfall and more afternoon rainfall than the rain gauge data, and they also miss the midnight rainfall minimum. These errors are mainly attributable to an underestimation of morning moderate and intense rains at coasts and an overestimation of afternoon–evening light rains on land. With a correction of the systematic bias, satellite products faithfully resolve the spatial patterns of normalized rainfall diurnal cycles related to land–sea contrast and terrains, suggesting an improved data application for regional climate studies. In particular, they are comparable to the rain gauge data in showing the linear reduction of morning rainfall from coasts to inland regions. TRMM is marginally better than CMORPH in revealing the overall features of diurnal cycles, while higher-resolution CMORPH captures more local details. All three datasets also present that morning rainfall is induced by the coastal convergence and mountain liftings of monsoon shear flow interacting with land breeze, which is mainly regulated by monsoon southwesterly winds in the northern part of the South China Sea.

1. Introduction

Diurnal cycle of rainfall (DCR), a fundamental periodic signal in the atmospheric variability, is extensively studied for a better understanding of the earth’s climate system and for an improved rainfall forecast (e.g., Dai 2001; Yang and Slingo 2001; Carbone et al. 2002; Dirmeyer et al. 2012; Yu et al. 2014). In recent decades, it is shown that the DCR exhibits pronounced regional and seasonal variations over the Asian monsoon region because it may respond to a variety of thermal/dynamic processes, evolution of convective systems, and associated atmospheric circulations at different space–time scales (Ohsawa et al. 2001; Nesbitt and Zipser 2003; Yu et al. 2007; Yuan et al. 2012a; G. Chen et al. 2014a). In particular, summer monsoon rainfall is substantial at coastal areas, where a large portion of the global population lives (Fig. 1a; Xie et al. 2006). The distinct patterns of the coastal DCR associated with land–sea contrast, topography, and monsoon activities are recognized as a key feature of the regional climate (Johnson 2011; Chen et al. 2013; X. Chen et al. 2014, 2016). As the DCR is also intricately linked to river runoff, evaporation, soil erosion, and other surface parameters at subdaily scales, it may play a crucial role in the hydrological cycle and ecological system (Kikuchi and Wang 2008; Li and Shao 2010; Reichle et al. 2017). Further studies of the detailed DCR at the monsoon coasts are thus important for agricultural activities, disaster prevention, and water resource management.

The south China coast (SCC) is a key region where the summer monsoon penetrates northward and affects the East Asian countries (Fig. 1; Luo et al. 2017). Recent studies show that the DCR at the SCC varies considerably in regions, seasons, and years because of land–sea contrast, complex terrains, and monsoon activities (Li et al. 2008; Chen et al. 2009, 2013; Huang and Chan 2012; S. Chen et al. 2016; Jiang et al. 2017). Morning rainfall usually occurs at the coastline and offshore, whereas
afternoon rainfall is predominantly on land (Wai et al. 1996; Chen et al. 2009; X. Chen et al. 2014). Rainfall diurnal amplitude increases remarkably in the presummer (May–June) season, associated with an active monsoon flow. The DCR is also strongly influenced by the convective systems that develop at midnight at the foothills of the Tibetan/Yungui Plateaus and then propagate eastward (Wang et al. 2004; Bao et al. 2011; G. Chen et al. 2014a; Jiang et al. 2017). On the other hand, the DCR is found to exhibit pronounced interannual–decadal variations over southern China (Yuan et al. 2013; Huang and Chen 2015). These suggest that the detailed features of the DCR at the SCC should be addressed as a key issue for revealing how various processes collectively regulate regional climate. Further studies of the DCR at the SCC provide insight into the physics of rainfall activities at monsoon coasts, which also serve as a benchmark to evaluate climate models (Satoh and Kitao 2013; G. Chen et al. 2014b).

In recent years, high-resolution satellite rainfall estimates have been widely used to study the finescale structures and properties of precipitation systems (Nesbitt and Zipser 2003; Hirose and Nakamura 2005; Yang and Smith 2006; S. Chen et al. 2016). However, satellite products may have noticeable biases and uncertainties because of the sensors’ limitations and different effectiveness for detecting various rain types (Dai et al. 2007). Although satellite data are usually gauge adjusted, it is necessary to evaluate their performance on capturing rainfall at subdaily scales (Janowiak et al. 2001; Sapiano and Arkin 2009; Shen et al. 2010). Zhou et al. (2008) show that satellite products have a poor representation of morning rainfall over low-lying plains, but they are comparable to the rain gauge data in showing the spatial patterns of diurnal rainfall amount, frequency, and intensity over China. Yuan et al. (2012b) found that satellite products tend to miss morning rainfall and overestimate afternoon rainfall over central China, with the largest underestimation coming from light morning rains in plains but the largest overestimation coming from afternoon rains in mountainous regions. The difference between station records and satellite data that depend on terrains and rain rates is also found over the Tibetan Plateau (H. Chen et al. 2012; Shen et al. 2014). Janowiak et al. (2005) noted that satellite-derived rainfall underestimates the amplitude of the diurnal cycle in the coastal southeastern United States. These previous studies strongly indicate that satellite products may face a challenge at the monsoon coasts, where the DCR patterns may vary highly in regions, seasons, and years. So far, the performance of satellite products in resolving the detailed DCR at the SCC remains unknown. Therefore, an intercomparison of surface and satellite observations helps the appropriate application of rainfall data over the coastal areas.

In this study, we examine the complexity of the DCR at a typical monsoon coast through evaluating two widely used satellite products against the rain gauge network at the SCC. Unlike previous studies that mostly focus on climate-mean features at a large scale, we pay more attention to the spatial patterns of the DCR adjacent to the coast and its seasonal changes, as well as interannual–decadal variations, which are related to the land–sea contrast, local terrains, and different atmospheric conditions. Another goal is to reveal the ability and uncertainty of satellite products in revealing the coastal DCR, pertaining to an improved data application over complex surfaces. Section 2 shows the datasets
and methods used in this study. Section 3 describes the variations of the DCR at individual gauge sites and derives an optimal measure for revealing DCR spatial patterns. Section 4 examines the dependence of the DCR on rain rate and on the distance to the coastline. Section 5 investigates the long-term variations of the DCR and associated possible causes. Finally, the conclusions are given in section 6.

2. Data and methods

The hourly rainfall data used in this study come from 86 routine surface stations in Guangdong Province of China (20.3°–25.3°N, 110°–117.3°E). These rain gauge sites are scattered over an area of ~180,000 km² at a spatial resolution of ~46 km (Fig. 1b). Such quality-controlled data can provide a reliable record of rainfall activities at high space–time resolutions. To examine the regional features with respect to coast, we group these 86 sites into three categories: near coastline, coast–inland transition zone, and inland region. As the sea breeze usually penetrates inland to a distance of 10–30 km with a maximum extent of 100–150 km (Simpson 1994; Miller et al. 2003), we apply the thresholds of 30 and 130 km to divide the three regions. As shown in Fig. 1b, there are 21 sites with a distance from the coast less than 30 km. These coastal sites are labeled 1–21 from west to east to reveal a possible effect of coastline geometry. There are 27 sites in the coast–inland transition zone, and they are labeled 22–58, according to their distance D from the coast (30 ≤ D ≤ 130 km). The other 28 sites are inland, with a distance from the coast greater than 130 km, and they are marked as 59–86. Most of the inland sites are located at the Nanling mountainous regions. We focus on the summer monsoon over southern China (Ding 1992).

The multisatellite merged rainfall estimates used in this study are the latest data from the Tropical Rainfall Measuring Mission (TRMM) 3B42 v7 and the Climate Prediction Center (CPC) morphing technique (CMORPH v1.0). They are derived by an optimal combination of high-quality microwave rainfall estimates and geostationary infrared rainfall estimates (Joyce et al. 2004; Huffman et al. 2007). TRMM has a resolution of 3-hourly and 0.25° longitude/latitude; CMORPH has an even higher resolution of 30 min and 8 km, which potentially resolves the finescale features of the DCR. Previous studies indicated that these two mainstream satellite products may outperform others in rainfall estimates over the regions with complex terrains (e.g., Zhou et al. 2008; Shen et al. 2010, 2014). For the in situ comparison to gauge data, the gridded satellite data of CMORPH and TRMM are interpolated to 86 gauge sites with inverse-distance weighting. The 30-min CMORPH data are summed to make hourly records. Both rain gauge and CMORPH data can be plotted at hourly intervals; their climate composites of diurnal cycles are smoothed by 3-h running mean to obtain coherent features and to match with TRMM data. Statistical analyses are made to the climate composites of three datasets at 3-hourly intervals. On the other hand, the Japanese 55-year global Reanalysis (JRA-55) is used to show the relevant atmospheric conditions and diurnal variability (G. Chen et al. 2014b). Local time (LT = UTC + 8 h) is applied in this study.

3. Seasonal change and regional features of DCR

a. Diurnal cycle of regional-mean rainfall amount

Before discussing the detailed patterns of DCR, we examine the diurnal variations of region-averaged rainfall amount, as in many validation studies. Rain gauge observations show that in presummer, hourly cumulative rainfall increases from 15 to 30 mm at 0200–0600 LT at the sites near the coastline (Fig. 2a). Rainfall reaches a maximum at 1100 LT, remains high through the day, and declines at night. Over the coast–inland transition (inland) region, rainfall exhibits a primary peak of 42 mm (34 mm) in afternoon and a secondary peak of 27 mm (24 mm) in the morning (Figs. 2b,c,e). The reduced morning rainfall on land manifests a possible effect of sea-breeze intrusion from 1200 LT to evening and a decayed influence of nocturnal convergence between land breeze and ambient onshore wind (Chen et al. 2015; X. Chen et al. 2016). Both satellite products tend to underestimate the morning rainfall over all three regions, with the largest bias at 0800 LT (Figs. 2a–e). The underestimation is largest near the coastline and gradually decreases from coastline to inland regions. Satellite products capture the afternoon peak (1500–1700 LT) of rainfall over coast–inland and inland regions, but they overestimate the rainfall amount from afternoon to late night (1400–0200 LT).

In midsummer, morning rainfall still exhibits a primary peak near the coastline in the rain gauge data (Fig. 2d). In contrast, it decreases from presummer to midsummer over the coast–inland and inland regions, where afternoon rainfall reaches a sharp peak, indicating a seasonal change of the DCR (Figs. 2e,f). Both satellite products capture the gauge-observed
afternoon rainfall, with a relatively higher peak in TRMM than in CMORPH. They report weakened morning rainfall in all three regions, similar to that in presummer. They also fail to capture the midnight minimum of rainfall observed by the rain gauge over the coast–inland and inland regions (Figs. 2b,c,e,f). Nevertheless, a diurnal range (maximum minus minimum) of rainfall in satellite estimates is comparable to that in the rain gauge data. On the other hand, CMORPH has an apparent deficiency of the daily mean rainfall near the coastline, compared to the rain gauge data (Figs. 2a,d).

Overall, the satellite data have a systematic bias for resolving the DCR at the SCC, as in central China (Zhou et al. 2008; Shen et al. 2010). One may get disappointed by a poor performance of satellite data at the coast, if the region-averaged climate diagrams like Fig. 2 are used for validation. A primary cause is that the rainfall amount and the DCR may vary considerably in sites, seasons, and years at the coast, which is not fully shown by regional mean diagrams. Previous studies show that the high-resolution satellite data potentially resolve the spatial patterns of the DCR at low and midlatitudes (Dai et al. 2007; Zhou et al. 2008; Chen et al. 2009). The application of satellite rainfall for regional climate studies is possible with an awareness of data preferences (Bao et al. 2011; Yuan et al. 2012a; G. Chen et al. 2012). It demands an in-depth analysis of the detailed patterns of the DCR at individual sites and their variations due to different surfaces or atmospheric conditions.

b. Spatial patterns of diurnal rainfall peak

Figures 3a and 3b show that rainfall tends to maximize at late night and morning at most of the gauge sites near the coastline (circles) during presummer, as in previous studies (Wai et al. 1996; Chen et al. 2009; Johnson 2011). Afternoon rainfall peak occurs at several sites (1–3, 17–19, and 21) at the western or eastern parts of the coastline with a nearly south–north orientation, where ambient southwesterly winds blow offshore (Fig. 1b). TRMM and CMORPH capture well the above features near the coastline, though errors appear at some
sites, as indicated by the color difference between site marks and the background map (Figs. 3a,b). Satellite data also show that the rainfall peak appears at 0200–0800 LT near the shore and shifts to 0800–1200 LT at 100–200 km offshore and to 1200–1600 LT over the open ocean. Such an offshore-delayed phase indicates that rain systems may initiate near the coastline and then propagate offshore (Aves and Johnson 2008; X. Chen et al. 2016).

Figures 3a and 3b also show that presummer rainfall usually maximizes at 1200–1800 LT at the gauge sites in the coast–inland transition zone (squares), with a slightly earlier peak at the sites relatively near the coast (22–45). Morning rainfall peak even appears at two sites (29 and 34) near the coastal center of heavy rains at 112°–113°E, where local mountains may favor nocturnal convection (Xie et al. 2006; Wang et al. 2014; X. Chen et al. 2016). Rainfall peak shifting from coastal to inland sites manifests the decay of coastal influence and sea-breeze front invasion. Two satellite products capture the afternoon-peak feature on land and its contrast to the morning peak near the coastline (dashed lines).

At inland sites (triangles), rainfall has an afternoon peak south of 24.5°N, while it maximizes in the morning at the northern six valley sites at ~25°N (Figs. 3a,b). Such a south–north difference of the DCR may reflect an effect of the Nanling Mountains, which divide cold and warm air in presummer (figure not shown). Intense convection or upward motion could be only present over the southern warm sector in the afternoon (Jiang et al. 2017). For the northern sites, the morning rainfall has been linked to nocturnal rain systems that propagate eastward at the lees of the Yungui Plateau (Chen et al. 2010; Bao et al. 2011; G. Chen et al. 2012; Jiang et al. 2017). Satellite products represent the eastward shift of nocturnal rainfall peak west of 112°E (shaded in blue in Figs. 3a,b), though the morning peak east of 112°E is less evident than the rain gauge data.

Figures 3c and 3d show that in midsummer, morning-peak rainfall is still observed at most of the coastal sites,
except for 1–3, 10–12, and 21. Afternoon-peak rainfall becomes dominant at all sites in the coast–inland transition and inland regions. Morning rainfall disappears at the northernmost sites, likely due to a seasonal decay of nocturnal migrating convection (G. Chen et al. 2012; Jiang et al. 2017). Satellite products capture well the dominant afternoon-peak pattern on land and morning-peak pattern offshore (cf. Figs. 3c,d and 3a,b). Satellite and rain gauge data also show that the along-coastline division between two different patterns shifts south from presummer to midsummer (dashed lines). These features suggest an evident seasonal change of the DCR patterns at the SCC.

c. Diurnal variations of rainfall amount, frequency, and intensity at individual sites

Rain gauge records and satellite data are used to further examine the detailed DCR at 86 sites. Figure 4a shows that in presummer, intense morning rainfall is observed at rain gauge sites 6–16 near the coastline. Rainfall peak appears at ~0600 LT at site 6 and gradually shifts to ~1100 LT at sites 9–12 to the east. Intense rainfall with a peak at 1000–1300 LT is also seen at three other sites (24, 29, and 34) in the adjacent north area. Such a coherent shift of diurnal phase is related to convective systems that usually propagate northeast in the steering southwesterly wind (G. Chen et al. 2012; Wang et al. 2014). The mountain–plains solenoid of coastal terrains enhances land breeze in the early morning and further enhances the convergence between monsoonal onshore wind and nocturnal offshore wind, which triggers coastal rainfall earlier (X. Chen et al. 2016; Chen et al. 2017). These morning-peak rains contribute considerably to the coastal rainfall hot spot at 112°–113°E (Fig. 1a). Both satellite products capture the regional center of morning rainfall and its phase shift (Figs. 4b,c). CMORPH markedly underestimates the rainfall amount at sites 8–12 in the Pearl River delta. This regional bias in CMORPH coincides well with the ending hour of daily rainfall accumulation given to the grids (22°–23°N, 113.5°–116°E) that differs from those surrounding grids (figure not shown), which may lead to failed calibration of satellite rainfall using the gauge records in the Pearl River delta.

Figure 4a shows another mode of coastal morning rainfall that strengthens in the early morning at sites 13–15 near small mountains at ~116°E. Such morning rainfall over the region with coastal orography (sites 13–15 and 6–7) is stronger than that over the region without coastal orography (sites 9–12), which may be related to the influence of the local mountain–plains solenoid. Unlike at sites 6–12, the peak hour of localized rainfall does not shift among sites 13–16. CMORPH captures such a local feature better than TRMM (Figs. 4a–c), indicating that the higher-resolution data offer an improved detection of terrain-dependent rainfall.

Figure 4a shows that obvious morning rainfall is also seen at many sites on land. The ratio of cumulative rainfall during 0500–1100 LT to that during 1400–2000 LT can be higher than 0.7 at two-thirds of the 86 gauge sites. Satellite products systematically underestimate morning rainfall, compared to the gauge data (Figs. 4b,c). The bias of TRMM (CMORPH) ranges from ~3.0 to ~5.8 mm (from ~4.1 to ~6.9 mm) at 0500–1100 LT. However, the spatial correlation of TRMM (CMORPH) with gauge data can reach 0.86–0.88 (0.74–0.79) at 0500–1100 LT, which is higher than that in other hours. Thus, satellite products are capable of capturing the spatial distribution of morning rainfall reasonably well, despite an underestimation of rainfall amount.

Figure 4a also shows that afternoon rainfall is pronounced at most sites on land, except for the northernmost sites (77–86) with relatively cold surfaces. Rainfall peak appears at 1400–1500 LT at sites 22–45, while it is delayed to 1600–1800 LT at sites 46–76. Both satellite products capture the regional differences of the peak hour, though they overestimate the rainfall amount in the afternoon and evening (Figs. 4b,c). The largest bias of TRMM (7.4 mm) occurs at 1700 LT, and that of CMORPH (3.9 mm) appears at 2000 LT. Meanwhile, the gauge-observed rainfall decays rapidly in the evening and drops to a minimum at midnight (Fig. 4a), which manifests the short-lived rain events (Li et al. 2008). Satellite products present a slower decay of evening rainfall than the gauge data and fail to capture the midnight rainfall minimum (Figs. 4b,c).

To clarify the possible causes of rainfall amount bias, we also examine the diurnal cycles of rain frequency (probability of ≥0.1 mm h⁻¹) and intensity (amount divided by occurrence). It is shown that the site-diurnal patterns of rain frequency and intensity are analogous to the patterns of rainfall amount (Figs. 4a,d,g). The pattern correlations between amount and frequency/intensity are estimated as ~0.83. The amplitudes of normalized diurnal cycles in Figs. 4d and 4g are also comparable. Thus, both rain frequency and intensity contribute to the DCR at the SCC. It somewhat differs from the previous findings over the other inland regions, where the DCR comes largely from rain frequency (Dai et al. 2007; Zhou et al. 2008). The difference is likely due to heavy rains that can contribute a large part of the rainfall amount over south China, particularly at coasts and windward mountains (Fig. 4g). Satellite products tend to report more rain occurrence in the afternoon/evening than the gauge data (Figs. 4e,f). Such an error in frequency explains
both the overestimation of afternoon rainfall amount and the failure of capturing the midnight rainfall minimum. Satellite data underestimate rain intensity at most sites, with the largest bias in the southern area (Figs. 4h,i).

The importance of rain intensity is further discussed in section 4b.

To depict an overall performance of satellite data for resolving both diurnal cycles and spatial patterns, we
estimate the correlation among the site-diurnal diagrams in Fig. 4. The pattern correlation of rainfall amount between TRMM (CMORPH) and gauge data is 0.83 (0.79). The correlation of rainfall frequency between TRMM (CMORPH) with gauge data is 0.75 (0.74), while that of rain intensity is 0.61 (0.58). Thus, TRMM is marginally better than CMORPH in revealing the overall spatial patterns of the DCR. The low correlation of rain intensity suggests an uncertain representation of intense rain events in satellite data (section 4b).

In midsummer, the signature of morning rainfall declines from the coast to inland and almost vanishes at northern sites (46–86), as shown in Fig. 5a. The seasonal decay of morning rainfall is evident at the sites on the southwestern slope of the inland mountains (triangles in Figs. 4a, 5a). It is related to the decay of low-level southwesterly winds from presummer to midsummer (Fig. 1b) that may result in weakened nocturnal migrating systems and orographic liftings (G. Chen et al. 2012; Chen et al. 2015; Jiang et al. 2017). In a robust contrast, afternoon rainfall becomes pronounced at most sites on land (22–86). Satellite products capture well both the pronounced afternoon rainfall and weakened morning rainfall (Figs. 5b,c). The pattern correlation of the DCR between TRMM (CMORPH) and the gauge data is 0.85 (0.79). Satellite data still overestimate afternoon rainfall occurrence and underestimate rain intensity (Figs. 5d–i), as in presummer.

It has been shown that over south China, the afternoon (morning) rainfall is mostly attributed to the short-lived (long lived) rain events with a large (small) radius (Li et al. 2008; G. Chen et al. 2012). Satellite-derived rainfall relies mostly on inferring the amount from infrared imagery or passive microwave data (Joyce et al. 2004; Huffman et al. 2007). As the infrared data are related more to cloud-top property than to precipitation, they have a relatively weak relation to precipitation on short time scales (Janowiak et al. 2005; Sapiano and Arkin 2009). Afternoon thunderstorms that last for a few hours and produce local rains are featured by the relatively broad anvil clouds with low brightness temperature in infrared images. The residual anvil clouds may also contaminate infrared rainfall estimates in the evening (Shen et al. 2010; Yong et al. 2014). Thus, the precipitation proxy using infrared data explains the rainfall overestimation and the relatively low spatial correlation with surface observation in afternoon–evening hours. Correspondingly, the rainfall adjustment to the gauge monthly amount may result in a weakened amount in the morning hours, but this does not affect the satellite data capturing the spatial pattern of morning rainfall associated with long-lived precipitation systems.

d. Bias-corrected diurnal cycles

In this section, we perform corrections to satellite products for a better application. The error of DCR patterns has been shown to come from the in situ daily mean rainfall bias and the diurnally varying systematic bias. To alleviate the effect of the first factor, we use the normalized DCR \( R_n \), which is defined by a ratio of hourly rainfall deviation \( R \) to the daily mean \( R_m \), that is, \( R_n = (R - R_m)/R_m \). Figures 6a–c show that the patterns of normalized DCR in presummer are more coherent than those in Figs. 4a–c and exhibit three major modes. The morning rainfall is prevalent at coastal sites with distinct local features associated with coastal geometry and topography (i.e., morning rainfall with phase shift at sites 6–12 and afternoon rainfall at sites 1–3). The afternoon rainfall, with a large amplitude ranging from \( \sim 0.8 \) to \( \sim 1.2 \), occurs at sites 22–76. The double-peak rainfall is seen at sites 77–86. Overall, the pattern correlation between the rain gauge and TRMM (CMORPH) reaches 0.88 (0.87), which is higher than that of 0.83 (0.79) before normalized. A relatively large improvement is seen in CMORPH, probably because the effect of its mean rainfall bias at sites 8–12 is alleviated (cf. Figs. 6b, 4b).

The 3-hourly statistics show that satellite data have a negative bias (from \(-0.12 \) to \(-0.25 \)) at 0500–1100 LT and a positive bias (from 0.06 to 0.21) at 1700–2300 LT (Fig. 6d). Figures 2a–c also show that the percentages of rainfall bias, relative to daily mean amount, are comparable in three regions, implying a systematic bias. We can further correct satellite data by removing such diurnally varying systematic bias. Figures 6e and 6f show that the bias-corrected normalized DCR data become highly similar to those of the rain gauge observations. In particular, the representation of morning rainfall and midnight rainfall minimum, as well as their variations among sites, is greatly improved in both satellite products. Their pattern correlations with the gauge data are significantly high, up to 0.94. Thus, the bias-corrected satellite rainfall can faithfully resolve the spatial patterns of the DCR at the SCC associated with complex coastline and local terrains.

Figures 7a–c show that in midsummer, both the enhanced afternoon rainfall and suppressed morning rainfall on land (sites 22–86) are clearly seen in three datasets in terms of normalized DCR. An underestimation (overestimation) of morning (afternoon) rainfall amplitude in satellite products is seen at most sites (Fig. 7d), as in presummer (Fig. 6d).
When this diurnally varying bias is removed, the patterns of normalized DCR become highly consistent with those of the gauge data, with the correlation coefficient up to 0.93 (Figs. 7a,e,f). Therefore, the bias-corrected normalized DCR offers a reliable measure for satellite data in revealing the complex patterns of the DCR and seasonal change at the SCC.

Because the systematic bias is a widespread phenomenon and can be estimated using coarse gauge networks, this correction method of satellite rainfall
may be applicable to other areas for climate and hydrological studies and water resource management.

4. Influence of land–sea contrast on the DCR

a. Dependence of the DCR on the distance from the coastline

In this section, we examine the importance of coastal rain systems relative to other processes on determining the DCR patterns. As shown in section 3, a primary feature of land–sea contrast is the morning rainfall that dominates near the coastline and decays inland. Here, we carry out a quantitative analysis on such a coast–inland reduction of morning rainfall. Figure 8a shows that normalized morning rainfall decays from ~0.5 to ~0.2 at gauge sites 6–55 in presummer. TRMM and CMORPH capture the rainfall variations among the sites, with small root-mean-square errors of 0.068 and 0.071, respectively. Figure 8c further shows that the linear reduction rate of morning rainfall is estimated as ~0.46 per 100 km in gauge data. The reduction rate in TRMM (CMORPH) is ~0.52 (~0.51) per 100 km, which is slightly faster than rain gauge records. The normalized morning rainfall drops to zero at ~65 km and to its regression minimum at ~120 km away from the coast in three datasets. Such a linear decay clearly manifests a competition between coastal morning-peak and inland afternoon-peak rain systems.

Three datasets also consistently show that the inland sites can be grouped into three types with different morning rainfall, as marked by “A” through “C” (Fig. 8c). Normalized morning rainfall is ~0.3 (near zero) at group A (group B) at the lee (windward) sides of mountain...
ranges, while it increases to $\sim 0.1$ at group C in the northern mountainous region. It seems that migrating nocturnal rain systems are competitive with afternoon-peak rain systems to determine the inland DCR with evident terrain-dependent features.

Figure 8b shows that the normalized morning rainfall declines from presummer to midsummer at most sites. The variations among sites also become small as afternoon rain events are dominant in midsummer. Satellite data capture well both the seasonal decay and site variations of morning rainfall, with an error of 0.080 (0.074) in TRMM (CMORPH). CMORPH tends to perform better than TRMM, likely because its higher resolution helps to resolve the local features induced by prevalent isolated rain events in midsummer. Figure 8d shows that the normalized morning rainfall declines to zero at $\sim 45$ km away from the coast, in contrast to that at $\sim 65$ km in presummer. The linear reduction rate of morning rainfall is estimated as $-0.47$ per 100 km in gauge data, which is comparable to that in presummer. Both satellite data capture well the reduction rate of midsummer morning rainfall. Thus, the competition between coastal and land rain events still seems evident in midsummer at southern sites. At inland sites, morning rainfall becomes suppressed and is less dependent on terrains than it is in presummer, likely due to the weakened lifting in the decayed south-westerly winds (Fig. 1b; Chen et al. 2017). Overall, bias-corrected satellite estimates are comparable to the rain gauge data in revealing the three major DCR modes and their seasonal change. A competition among these modes is shown to greatly determine the spatial patterns of the DCR at the SCC.

b. Dependence of the DCR on various rain rates

Another important feature of the coastal rainfall events is their relatively high rain intensity, compared to inland rainfall events (Figs. 4g, 5g). We estimate the seasonal cumulative rainfall of various rain rates to depict their contribution to the DCR. Figure 9a shows that in the morning hours, the gauge-observed cumulative

![Fig. 7. As in Fig. 6, but for the midsummer.](image-url)
rainfall decreases exponentially at equant bins from light to intense rains, as in Yu and Li (2012). On average, light rains contribute 52.4% of morning rainfall, while moderate-to-intense rains explain 47.6%. The moderate-to-intense rains explain ~60% of morning rainfall at coastal sites 6–16, while they reduce to ~40% at inland sites 46–86 with a rate of ~20.1% (100 km)^{-1}. In particular, intense rain events account for ~22% of morning rainfall amount at the coast but only ~9% inland. Thus, moderate-to-intense rains are a primary factor responsible for the land–sea contrast of morning rainfall.

Satellite products underestimate moderate-to-intense rains at most sites, resulting in the systematic underestimation of morning rainfall (Figs. 9b,c). The ratio of moderate-to-intense rains to morning rainfall is 41.6% (38.1%) in TRMM (CMORPH), which is smaller than that in the gauge data (47.6%). Figures 9b and 9c also show that the large underestimation of moderate-to-intense rains mainly occurs at the sites near the coastline or windward mountains, where the local rainfall maxima occur (Fig. 4a). It is expected, as satellite rainfall is adjusted using gauge analysis at relatively coarse grids. The relevant bias in gauge analysis at relatively coarse grids. The relevant bias in TRMM (CMORPH) averaged over sites 1–45 is ~33.4 mm (~52.3 mm). The bias of CMORPH is most evident at sites 9–12 and 30, likely due to the calibration error in the Pearl River delta. The fraction of moderate-to-intense rains decays from coastal to inland regions at a rate of ~16.7% (~11.1%) (100 km)^{-1} in TRMM (CMORPH), which is slower than that in the gauge data (~20.1%). Overall, TRMM is better than CMORPH for resolving the intense coastal rains and their linear decay in the morning hours.

Figure 9d shows that light rains are pronounced in the coast–inland and inland regions in the afternoon hours, in relation to short-duration showers. The coast–inland reduction of moderate-to-intense rains is not evident. Two satellite products have a positive bias of light rains at most sites (Figs. 9e,f). The positive bias of light rains and negative bias of intense rains are more evident in CMORPH than in TRMM. TRMM instead has an obvious bias (>20 mm) of moderate rains at one-third of the sites. These features help to explain the systematic
overestimation of afternoon rainfall in the satellite data (Fig. 4c).

In midsummer, the rainfall decays in all three cat-
egories in the morning (Fig. 10a). Moderate-to-
intense rains contribute 46.5% of morning rainfall,
which is comparable to that in presummer. They are
also more evident at coastal sites (~50%) than at in-
land sites (~40%), with a reduction rate of ~8.6%
(100 km)~1. Figures 10b and 10c show that satellite
products underestimate moderate-to-intense morning
rains, with a relatively large bias at southern sites. As
for the afternoon rainfall, both satellite products
overestimate light rains, with a relatively large bias at
inland sites (Figs. 10d–f). They tend to underestimate
the moderate rains, which differs from the overestimation
of moderate rains in presummer. Overall, the errors of
satellite products are mainly due to an underestimation
of morning moderate-to-intense rains, especially near the
coastline, and an overestimation of afternoon–evening
light rains on land. Therefore, the satellite-derived rain-
fall should be used to study the DCR patterns at coasts
with caution of their dependence on rain rates.

5. Long-term variations of regional DCR modes
and possible processes

a. Interannual variations of the DCR revealed by
three datasets

It is well recognized that the DCR not only exhibits
spatial patterns, but also undergoes evident interannual–
decadal variations over southern China (G. Chen et al.
2012; Yuan et al. 2013; Huang and Chen 2015). Although satellite data, in revealing the climate-mean DCR, are widely validated (e.g., Zhou et al. 2008), their performance in capturing the long-term variations of the DCR at the coast is less studied. Meanwhile, a variety of physical processes have been linked to the spatial patterns of the DCR from a climate-mean perspective (Chen et al. 2009, 2013; Huang and Chan 2012; X. Chen et al. 2014, 2016; Jiang et al. 2017). However, it is still unclear how the processes regulate the long-term variations of the DCR. In this section, we use a 17-yr archive of gauge data, satellite products, and new-generation reanalysis to examine the interannual variations and decadal trend of the regional DCR modes, with an emphasis on the primary rainy season in presummer.

Figure 11a shows the variations of morning rainfall observed by the rain gauge during 1998–2014. Coastal morning rainfall exhibits a pronounced interannual variation, with a relatively large amount in 1998, 2001, 2003, 2005–08, and 2014. The standard deviation averaged at sites 6–16 reaches 181 mm (Fig. 11g), which is comparable to ~45% of mean rainfall (406 mm). Large interannual variation is also observed at several sites in the coast–inland transition zone near windward mountains (24, 29, 34, 45, 56, and 58). The standard deviation at these orographic rain hot spots is estimated at 184 mm, which is much higher than that at other surrounding sites (104 mm). Extreme rainfall above 700 mm occurs in 1998, 2005, 2006, 2008, and 2010, in a robust contrast to the background rainfall of 261 mm (Fig. 11a). Figures 11a and 11g also show that the interannual variation of morning rainfall is relatively small at the northernmost 10 sites. Thus, the variance of morning rainfall reduces from the coast to inland, with an evident effect of land–sea contrast and local terrains. Meanwhile, strong rainfall mainly occurs at the coastal sites in 2008, while it appears at the inland sites in 2005 and 2010, suggesting the regional features of extreme heavy rains.

Fig. 10. As in Fig. 9, but for midsummer.
FIG. 11. Interannual variation of the presummer rainfall amount in (a)–(c) morning and (d)–(f) afternoon hours at 86 gauge sites. The site-diurnal pattern correlation coefficients between rain gauge and satellite products are labeled in the upper-right corner of the figures. (g)–(j) Standard deviation and correlation with gauge data at individual sites. The dashed lines denote the confidence levels of 0.05 and 0.01. The triangles denote the sites adjacent to the windward mountains of the southwesterly monsoon.
Figures 11b and 11c show that two satellite products capture well the interannual variation of morning rainfall, despite an underestimation of the mean rainfall amount. They present strong rainfall in 1998, 2001, 2003, 2005–08, and 2014, consistent with the gauge data. The pattern correlation between TRMM (CMORPH) and the gauge data at 86 sites in 17 years reaches 0.84 (0.77).

Figure 11g shows that satellite products somewhat underestimate the interannual variance, compared to the gauge data, especially at coasts and windward-mountain sites, though they present similar spatial variation among the 86 sites. The temporal correlation of the satellite products with the gauge data at individual sites is usually as high as ~0.8, above a significance level of 0.01. TRMM performs better than CMORPH, with a marginally higher correlation coefficient at most of the sites.

As for afternoon rainfall, both rain gauge and satellite data exhibit pronounced interannual variation, especially in the coast–inland transition zone (Figs. 11d–f). Rainfall is enhanced in the recent years of 2005–14 and thus undergoes a decadal change (Huang and Chen 2015). Weak rainfall appears in 1999, 2000, 2002, and 2004, while strong rainfall mainly occurs in 2005, 2006, 2008, 2010, and 2014. Such variations are seen at most sites and have a comparable standard deviation of ~125 mm, suggesting that long-term variations of afternoon rainfall are probably subjective to the atmospheric conditions at large scale. The localized interannual variance at the sites near windward mountains is less evident than that of morning rainfall. Satellite products capture the rainfall variations at most sites with comparable standard deviation (Fig. 11h) and high correlation (Figs. 11e,f,j). Thus, it is concluded that satellite products faithfully resolve the DCR’s interannual variations and their regional features, which supports a reliable application of satellite-derived rainfall for climate research.

b. Possible processes responsible for long-term variations of three DCR modes

In previous sections, we have identified three major DCR modes: morning rainfall at the coast, afternoon rainfall on land, and nocturnal rainfall in the northern inland region. Here, we further investigate the interannual variations and decadal trend of these DCR modes, as well as related physical processes. As shown in Fig. 12a, the variations of morning rainfall at sites 6–16 represent the dominant DCR mode at the coast. Gauge-based rainfall amount increases considerably (~130%) in 1998–2008. The increase rate reaches 33.0 mm yr$^{-1}$,
which is much higher than 23.6 mm yr\(^{-1}\) of afternoon rainfall (cf. Figs. 11a,d). It reaches a peak of 712 mm in 2008 and then reduces to a relatively low amount of ~385 mm in 2009–14. TRMM captures such long-term variations of coastal morning rainfall despite a slight underestimation of mean amount.

Climate-mean analyses have noted that the land–sea breeze and prevalent monsoon flow help to produce the morning-peak rainfall at the SCC (Ohsawa et al. 2001; Chen et al. 2013; Ruppert et al. 2013; X. Chen et al. 2016). To clarify the mechanisms regulating the long-term variations of rainfall, we examine the atmospheric conditions over the coastal region of the SCC. We focus on the horizontal winds and convergence at 1–2 km above ground level (AGL) as a good indicator of monsoon flow and those below 1 km AGL relating to land–sea breeze (X. Chen et al. 2014). Figure 12b shows that the coastal convergence at 875–800 hPa increases in 1998–2008 and decays to near zero after 2009. The variation coincides well with that of morning rainfall in Fig. 12a, with a high correlation coefficient of 0.71. The intensified convergence mainly occurs at the coast in the monsoon shear flow, which is associated with strong southwesterlies in the north part of the South China Sea (Fig. 13a). It is largest in the morning when monsoon southwesterlies are diurnally enhanced (not shown). The induced low-level ascent is thought to support nocturnal convective systems that are usually initiated at elevated layers. The convergence in monsoon shear flow has been linked to the rainfall variation over south China (Chen et al. 2011). Such a process is thus most effective in the morning as a response to the diurnal cycle of monsoon flow.

Figure 12b shows that the coastal convergence below 925 hPa exhibits no decadal trend but has an evident year-to-year variation, with intensification in 1998, 2001, 2003, 2005, and 2008. In those years, it has a high resemblance with the positive anomaly of detrended rainfall (black line minus dashed line in Fig. 12a). Figure 13b shows that the convergence anomaly maximizes
near the shore and results from an intensified meridional gradient of the southwesterly monsoon at the SCC. Such a gradient of the onshore ambient wind speed is induced by land–sea friction difference and coastal mountains (X. Chen et al. 2016; Chen et al. 2017). The convergence is stronger at 0800 LT than at other hours (not shown), and it presents an enhanced confluence of onshore monsoon and land breeze. Given that land breeze is a well-established local mode, the long-term variation of the coastal convergence in both the boundary layer and the elevated layers is mostly controlled by the monsoon flow (Fig. 12b). The wind speed may also regulate the mountain lifting, with strong southwesterly winds leading to intense orographic rains in 1998, 2005, 2006, 2008, 2010, and 2014 (Figs. 11a, 12b). The above findings extend a 3-yr mean analysis of X. Chen et al. (2014) and demonstrate that morning rainfall increases considerably at coasts and windward mountains in the years when the onshore winds are enhanced.

Figure 12c shows the interannual variation of the afternoon–evening rainfall at sites 46–76, which represents the afternoon-peak DCR mode on land. Rainfall is relatively weak (~274 mm) before 2004 and becomes more pronounced (~390 mm) afterward. Similar variations are seen in morning rainfall but at a much smaller amplitude (cf. Figs. 11a,d). Afternoon convection is related to the large-scale atmospheric circulation and the thermal instability in weak gradient flows (Huang and Chen 2015; Jiang et al. 2017). Figure 12d shows that the large-scale vertical motion at 1400 LT exhibits interannual variation highly similar to that of afternoon–evening rainfall. The correlation coefficient between rainfall and preceding 500-hPa vertical motion is as high as 0.84. In particular, rainfall is strong in 2005, 2006, 2008, and 2014, when the vertical motion at 500 hPa is enhanced and much stronger than that at 850 hPa. Rainfall variation is thus related to the vertically enhanced rising motion that supports the growth of moist deep convection. Figure 13c shows that the favorable environment is a large-scale anomalous cyclonic circulation over southeastern China and an anticyclonic circulation over the South China Sea that enhances the southwesterlies at the SCC. Such a large-scale pattern expresses a thermal contrast between the subtropical Asian continent and adjacent oceans (Chen et al. 2011; Huang and Chen 2015). Figure 13c also shows that the strength of convection maximizes at land grids along ~23.75°N, likely due to an effect of the warm sector of south China (Jiang et al. 2017), while it is relatively weak at coastal grids.

Figure 12e shows the interannual variation of nocturnal rainfall at northern inland sites. Rainfall exhibits a decadal increase of ~70% during 1998–2010 and reaches a maximum of 340 mm in 2010. The increase rate is estimated as 11.3 mm yr⁻¹ and is much higher than that of afternoon rainfall (7.7 mm yr⁻¹). As shown in previous sections and other studies, the nocturnal rainfall at these sites is related to the convective systems that propagate eastward along a quasi-stationary front or shear line (G. Chen et al. 2012; Jiang et al. 2017). Figure 12f shows that the meridional temperature gradient and low-level vorticity, as an indicator of the frontal strength, display interannual variation similar to the morning rainfall, with correlation coefficients of 0.70 and 0.82, respectively. In particular, the product of two terms maximizes in 2010 and corresponds to the strongest rainfall. The strength of the frontal zone (shear line) in the northern region thus explains the long-term variations of nocturnal rainfall. The favorable condition is the anomalous southwesterly winds at the SCC and the northeasterly winds in central China that enhance the wind shear in southwest–northeast zone (Fig. 13d). The anomalous southwesterly winds in Fig. 13 are expected to enhance the moisture transport and convergence for producing rainfall. It is also noted that the shear flow of a southwesterly monsoon mainly affects the coast in 2008, while it extends northward in 2010 (figure not shown). This corresponds to the years of decadal shift of morning rainfall that differ in coastal and northern regions.

6. Summary and discussion

Using a 17-yr archive of finescale rain gauge and satellite data, we investigate the diurnal cycle of rainfall at the south China coast. Unlike many previous studies focusing on the large-scale climate-mean DCR, we emphasize the spatial patterns, seasonal change, and interannual–decadal variations of the DCR that strongly depend on the coast, terrains, and monsoon activities. The major findings are summarized below.

1) Performance of CMORPH and TRMM in representing DCR is verified through comparing the hourly data of 86 gauge sites. It is shown that both satellite products tend to underestimate the morning rainfall at coastal sites and overestimate the afternoon rainfall at inland sites. They also fail to capture the rainfall minimum at midnight on land. The primary causes involve a negative bias of morning moderate–intense rains near the coasts and a positive bias of afternoon–evening light rains on land, probably due to the effect of anvil clouds from afternoon convection on infrared rain estimates. These errors vary from presummer to midsummer, as morning rainfall decays and afternoon rainfall becomes pronounced. Satellite products capture the spatial pattern of...
morning rainfall better than that of afternoon rainfall, probably because of a tenuous relation between infrared data and short-duration rain events that are mostly prevalent in the afternoon.

2) Despite the above errors, satellite data resolve well three regional DCR modes: morning rainfall at the coast, afternoon rainfall on land, and nocturnal rainfall in the northern inland region. In particular, satellite products detect the pronounced morning rainfall at the coastal sites with high rainfall. They also present the coherent shift of the diurnal phase at the heavy rain centers near coastal mountains, consistent with gauge records. Afternoon rainfall is observed at several coastal sites at the north–south-orientated coastline, where ambient southwesterly winds blow offshore. Satellite products also present that afternoon rainfall becomes more pronounced on land from presummer to midsummer. All three datasets agree in showing that the nocturnal rainfall associated with migrating systems is evident at the northernmost sites in presummer but disappears in midsummer. These validation results regarding DCR patterns differ from the commonly used regional-mean diagrams that likely suggest a poor performance of satellite data.

3) To alleviate the effect of both the daily mean rainfall bias and diurnally varying systematic bias, the bias-corrected normalized rainfall is proposed to depict the DCR. Based on the bias-corrected data, the pattern correlation of satellite data with rain gauge records reaches a significant high value of ~0.93. Satellite patterns thus can faithfully resolve the spatial patterns of the DCR associated with land–sea contrast and local terrains, suggesting an improved data usage. In particular, they capture well the linear decline of morning rainfall from coastal to inland regions at a distance of ~120 km. The competition and seasonal change of the three major diurnal modes are also found to explain the spatial–temporal patterns of the DCR over southern China. Overall, TRMM is marginally better than CMORPH in revealing the DCR’s general features, while CMORPH, at a higher resolution, captures more local details.

4) Rain gauge and satellite data are also shown to be comparable in revealing the interannual variation and decadal trend of regional DCR modes over southern China. Morning presummer rainfall has pronounced interannual variation, with the largest variance near the coasts and windward mountains, implying orographic rainfall hotspots. Rainfall amount increases ~130% during 1998–2008 and declines to a relatively low value after 2009. Such long-term variations of morning rainfall are found to be associated with the coastal and mountain liftings of monsoon shear flow and land breeze. The coastal convergence at elevated layers has a good association with both the interannual variation and decadal trend of coastal morning rainfall, while that in the boundary layer accounts for a part of the interannual variance. The afternoon rainfall has pronounced interannual variation on land and exhibits a decadal shift in 2005, which is related to the midtropospheric ascent due to a large-scale cyclonic (anticyclonic) circulation over southeastern China (South China Sea). As for the nocturnal rainfall at the northernmost sites, it undergoes a moderate increase of 70% during 1998–2010. It is closely associated with an enhanced front (shear line) that favors eastward-moving nocturnal convective systems.

In this study, a systematic bias of rainfall amount is seen in CMORPH and TRMM, as in previous studies (e.g., Zhou et al. 2008; Yuan et al. 2012b). However, it should not deny the prospect of data application, even at the monsoon coasts where the diurnal cycles are highly complicated. The bias-corrected satellite data resolve well the spatial–temporal variations of three major diurnal modes; they also capture many finescale DCR features that strongly depend on coast geometry, local terrains, and monsoon activities. Recently, H. Chen et al. (2016) compared the hourly rainfall between station records and satellite data over central–eastern China from the perspective of a regional rainfall event. They found that the spatial–temporal variations of event frequency and intensity are quite consistent among different datasets; the widely recognized bias of afternoon rainfall in satellite data is much less obvious. Here, a practical method of bias-corrected normalized diurnal cycle may be used to alleviate the effect of systematic bias. It serves as a variable suitable for resolving the finescale features of coastal DCR and, thus, adds credit to satellite data application for regional climate research.

Previous studies have attributed the three major DCR patterns to a series of physical processes over southern China. The morning-peak coastal rainfall may be induced by the lifting due to differential surface friction and mountains at the coast, which can be enhanced by the land–sea breeze interacting with prevalent monsoon flow (Ohsawa et al. 2001; Ruppert et al. 2013; X. Chen et al. 2016). The nocturnal rainfall with an eastward-delayed phase occurs at the lee of plateaus, where the mountain–plains solenoid and diurnally varying winds can regulate the low-level ascent, moisture transport, and convective instability (Chen et al. 2010; Bao et al. 2011; Huang and Chan 2012; Chen et al. 2013; G. Chen et al. 2014a; Jiang
et al. 2017). The afternoon-peak rainfall may form on land as a response to the thermal instability and moist static energy induced by daytime solar radiation and topographic inhomogeneity (Fujinami et al. 2005; Yuan et al. 2012a; Satoh and Kitao 2013). Here, we see that the competition of these three modes and their seasonal change greatly determines the spatial distributions of the DCR at the SCC. Further studies may provide more insights into how the rainfall systems respond to the above physical processes associated with land–sea contrast, local terrains, and different atmospheric conditions.

Another interesting feature is the pronounced interannual variations of different regional DCR modes observed at monsoonal coasts. A variety of physical processes had been proposed for producing the climate-mean DCR modes and heavy rain cases (Wai et al. 1996; Aves and Johnson 2008; Chen et al. 2009; G. Chen et al. 2014a; X. Chen et al. 2014, 2016; Chen et al. 2015; Jiang et al. 2017). In this study, these relevant processes are shown to vary considerably at interannual–decadal scales. It also indicates that the general circulations, such as the East Asian summer monsoon, and atmospheric thermodynamic conditions may play a role in regulating the regional DCR patterns and their long-term variations (Yuan et al. 2013; Chen et al. 2013; G. Chen et al. 2014b; Huang and Chen 2015). A crucial issue is the strong interactions between regional and large-scale forcings that vary in specific locations with complex terrains. Thus, further analyses on both typical rainfall cases and climate events are warranted for further understanding of the preferred hour, locations, and trend of extreme heavy rains associated with large-scale climate change.

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