



Article Morphology of Rain Clusters Influencing Rainfall Intensity over Hainan Island

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Abstract: Continuous observations from geostationary satellites can show the morphology of precipitation cloud systems in quasi-real-time, but there are still large deviations in the inversion of precipitation. We used binary-connected area recognition technology to identify meso-β-scale rain clusters over Hainan Island from 1 June 2000 to 31 December 2018, based on Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM data. We defined and statistically analyzed the parameters of rain clusters to reveal the typical morphological and precipitation characteristics of rain clusters, and to explore the relationship between the parameters and rainfall intensity of rain clusters. We found that the area and long axis of rain clusters over land were larger than those over the ocean, and that continental rain clusters were usually square in shape. Rain clusters with a larger area and longer axis were concentrated on the northern side of the mountains on Hainan Island and the intensity of rain was larger on the northern and eastern sides of the mountains. The variation of continental rain clusters over time was more dramatic than the variation of oceanic clusters. The area and long axis of rain clusters was larger between 14:00 and 21:00 from April to September and the long axis of the oceanic rain clusters increased in winter. There were clear positive correlations between the area, long axis and shape of the rain clusters and the maximum rain rate. The area and long axis of continental rain clusters had a higher correlation with the rain rate than those of oceanic clusters. The establishment of a relationship between the morphology of rain clusters and precipitation helps us to understand the laws of precipitation and improve the prediction of precipitation in this region.

Keywords: Hainan Island; morphological characteristics; precipitation characteristics; sea–land differences

1. Introduction

Hainan Island is located in the tropical South China Sea at the southern tip of mainland China and has abundant water vapor throughout the year. As a result, it has one of highest annual rainfalls in China [1]. Hainan Island and the surrounding areas are affected by weather systems—such as monsoons, tropical cyclones, low-pressure troughs, fronts and jets—and the characteristics of precipitation in this region are complex [1–3]. Hainan Island is located at the intersection of the southern edge of the East Asian monsoon region and the Northwest Pacific and therefore the physical parameters—such as the potential temperature, wind field, vorticity and precipitation—of the island and surrounding areas are important in monitoring the onset of the Chinese summer monsoon and tropical cyclones [4,5]. An in-depth study of the characteristics of precipitation patterns in this region and the surrounding areas helps us to understand precipitation patterns in this region and improve the forecasting of meteorological disasters in East Asia [6,7].



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). China has completed many observational experiments in the South China Sea and South China since the 1970s. These experiments have laid the scientific foundations for forecasting rainstorms in the South China Sea and South China and established a series of ground- and ship-based observational datasets [8–12]. However, these datasets lack long-term, large-scale observations and can only be used for individual case studies. Our understanding of the characteristics of precipitation over Hainan Island and its surrounding areas is still insufficient. The rapid development of satellite-detection technology over the last 20 years means that we can now carry out large-scale continuous monitoring of cloud and precipitation systems without being restricted by the natural geographical conditions, effectively overcoming the disadvantages of ground-based observations. The observed precipitation data has a wide coverage, long duration and high spatial accuracy [13].

Existing studies use multi-year average grid-based satellite data or pixel-level products to obtain direct statistics to study the temporal and spatial characteristics of precipitation, without consideration of the integrity and continuity of the precipitation system. If an area of continuous precipitation is identified as a rain cluster, then the systematic characteristics of the rain cluster (such as the spatial form and total precipitation) can be obtained [14,15]. Hamada et al. [16] showed that the relationship between heavy rainfall and deep convection was not strong at the scale of rain clusters. Chen et al. [17] found that slender and chunky rain clusters had the largest rain intensity and moderate 3D rain clusters had the lowest rain intensity over the Tibetan Plateau.

Stationary meteorological satellites can effectively observe the appearance of clouds but provide large errors in the estimation of precipitation intensity. Theoretically, the appearance of clouds is related to the internal movement of the atmosphere, radiant heating and the water vapor phase transition in the atmospheric circulation, which is also related to precipitation. Early data mainly used an artificial classification of rain clusters. Gagin et al. [18] and Tsonis et al. [19] used ground-based radar data to study the relationship between the area of rain clusters and precipitation. Song et al. [20] estimated efficient areas of precipitation using S-band dual-polarization radar measurements and yielded a rigorous comparison in statistical and machine learning. Capsoni et al. [21] and Awaka [22] found a relationship between the characteristic radius and peak rainfall rates of rain clusters. For large amounts of satellite data, Nesbitt et al. [23] used the ellipse-fitting area method to fit rain clusters and then discussed the morphological differences between rain clusters over land and rain clusters over the ocean. Liu et al. [24] found that convective systems over land had a larger area and a more circular shape than convective systems over oceans. In addition, more shallow convective systems appeared over the ocean and coastal areas.

As a result of the unique geographical location and topography of Hainan Island, the thermodynamic conditions are different over the land and the ocean and the precipitation has regional characteristics [1,25–29]. At present, we have an insufficient understanding of the scale of rain cluster precipitation characteristics of Hainan Island and its surrounding areas and especially a lack of understanding of the morphological characteristics of rain clusters. Our study aims to reveal the relationship between the morphological characteristics of rain clusters and the intensity of precipitation.

2. Data and Methods

2.1. Data

The Global Precipitation Measurement (GPM) project is carried out by the National Aeronautics and Space Administration (NASA) [30]. Its core satellite was launched on 27 February 2014 and satellite precipitation observations have changed from the original Tropical Rainfall Measuring Mission (TRMM) satellites to GPM satellites. The GPM products are divided into four levels based on different retrieval algorithms. The Integrated Multi-satellitE Retrievals for GPM (GPM IMERG) is a three-level product representative of the GPM. It makes full use of the remote-sensing detection data from GPM satellites and various mature retrieval algorithms for the TRMM satellites to provide satellite-retrieval precipitation products with a temporal resolution of up to 30 min and a spatial resolution of $(0.1^{\circ} \times 0.1^{\circ})$.

Based on the number of precipitation data calibrations, IMERG provides three types of precipitation products: "Early Run", "Late Run" and "Final Run". The IMERG generation system runs once in the real-time phase to obtain the Early Run product. After obtaining multiple data points, it is then run again to obtain the Late Run product. The Early Run and Late Run are quasi-real-time products and are released after 4 and 12 h of observations, respectively. On the basis of the Late Run, more sensor data sources are introduced for calibration to obtain a higher precision research product (Final Run), which is usually released after 3.5 months of observations [31].

Preliminary assessments of the GPM IMERG product have been made in many regions. The detection of precipitation by the GPM satellites has been significantly improved relative to the TRMM satellites and it has a better correlation with observational data in China [32]. Feng et al. [33] used GPM IMERG satellite precipitation data and geostationary meteorological satellite infrared brightness temperature data to build a long-term (2000–2019) global high-resolution mesoscale convective system database, in order to study the characteristics of global mesoscale convective systems. Mahmoud et al. [34] evaluated the accuracy of GPM IMERG V06 (Early, Late, and Final) satellite precipitation products at high latitudes in Finland and found that IMERG-Final satellite precipitation products performed best in its high correlation with ground observation.

We used the GPM IMERG HDF5-formatted level 3 satellite data product, Final Run, from 1 June 2000 to 31 December 2018 and the version IMERG V06B algorithm [35,36]. The GPM IMERG series products were downloaded from NASA's official website (https://gpm.nasa.gov/data/directory, accessed on 24 June 2021). We used terrain, height and digital elevation model (DEM) data provided by the National Geophysical Data Center with a spatial resolution of 1/30°. The National Geophysical Data Center DEM data can be obtained from the United States Geological Survey website (www.ngdc.noaa.gov/, accessed on 24 June 2021).

2.2. Methods

Hainan Island is elliptical in shape with its long axis running from the northeast to the southwest. The terrain is high in the middle and surrounded by low terrain on all sides. The highest area is Wuzhi Mountain in the center (the main peak is 1867 m above sea level). This region consists of mountains, hills, platforms, plains and terraces, which form a layered landform surrounding the central mountains [37–40]. The research area was located at (18°03′–20°15′N, 108°27′–111°9′E) and covered Hainan Island and the surrounding offshore areas. The selected range of rain clusters (located at 15–23°N, 105–114°E) was larger than the research area to reduce the impact of truncated rain clusters.

Because the selected area covers Hainan Island and the surrounding area, it is more appropriate to study mesoscale and small-scale rain clusters, although the satellite data are not precise enough and light rain clusters are susceptible to interference from other factors. We therefore mainly analyzed the characteristics of meso- β -scale rain clusters (20–200 km). The connected domain recognition technology widely used in the field of image recognition was employed to identify the meso- β -scale rain clusters. We mainly implemented it through the Open Source Computer Vision Library (OpenCV) developed by Intel. OpenCV provides interfaces for C++, Python, Java and MATLAB, etc., and includes rich libraries of image-processing and computer vision functions [41–43]. The satellite images were first binarized—that is, the precipitation area (set to 1) and the no precipitation area (set to 0) were distinguished. We then called the function "findContours" in OpenCV to find all enclosed areas and identified each connected domain as a rain cluster. The total number of mesoscale rain clusters calculated was 231,664 and these clusters were combined with DEM topographic data to distinguish between oceanic and continental rain clusters by distinguishing their central coordinates. There were 113,006 oceanic rain clusters and 118,658 continental rain clusters.

Figure 1 shows a topographic map of Hainan Island and its surrounding areas and the spatial distribution of the rain clusters. Most areas of Hainan Island are >100 m above sea level and there are many mountains with steep terrain >500 m above sea level in the central and south-central parts of the island, including the Wuzhi and Limu mountains. The northeast and coastal areas have lower elevations and flatter terrain (Figure 1a). Rain clusters mostly occur in the central area and the coastal areas to the east, north and southwest. Most occur in the ocean north of Hainan Island and the rain clusters on the island are concentrated on the northern side of the central mountain (Figure 1b), which may be caused by the uplift in topography. The sample number for each grid point is 240–720, which meets the needs of the statistical analysis.



Figure 1. (a) Topography of Hainan Island region (units: km), (b) frequency of rain clusters (bin: 0.1°).

To describe the identified rain clusters, we constructed the minimum bounding rectangle (MBR) of the rain clusters. Firstly, we determined the convex vertices of the polygon composed by the pixels. We then selected four endpoints and constructed four tangents of the polygon through these four endpoints. These four tangents formed the bounding rectangle of the rain cluster. If a tangent coincided with the edge of the polygon, then the area of the rectangle was calculated. We selected different endpoints by continuous rotation and then calculated the area of different rectangles. The rectangle with the smallest area was regarded as the MBR of the rain cluster [44,45].

We also defined some morphological and physical parameters (Table 1). The first five parameters were morphological parameters, among which "Angle" is the rotation angle of the long axis of the MBR; the angle between the long axis and due north. The clockwise direction is positive and the range is (0, 180). "*WL*" represents the shape of the rain cluster, which is the ratio of the short axis to the long axis with a range of (0, 1). If *WL* is closer to 1 then the rain cluster tends to be square, and if it is closer to 0 then the rain cluster is closer to a linear system. The remaining four parameters are physical and include the central position of the rain cluster, the average rain rate and the maximum rain rate, which reflect the geographical location of the rain cluster and the intensity of the rain.

Figure 2 shows two examples of mesoscale rain clusters formed at 16:00 on 27 August 2006 and 12:30 on 12 August 2000 (Beijing Time, UTC + 8). Table 2 lists the morphological and physical parameters of the two rain clusters. The morphological parameters *L*, *W*, Angle, *WL* and *S* of the first rain cluster were 154.58 km, 144.04 km, 108.44°, 0.932 and 14,437.8 km², respectively. The long and short axis of the rain cluster were similar and *WL* was close to 1. The cluster is presented in an approximately square shape. The rotation angle of the long axis was >90°, indicating that the long axis of the MBR was along the east–south direction. The central latitude and longitude were (109.67°E, 18.80°N). The rain cluster was located over Hainan Island and was therefore a continental rain cluster. The mean and maximum rain intensity were 3.52 and 16.22 mm/h, respectively.

In the second example, *L* was 199.98 km, *W* was 66.66 km and the long axis was due east; *WL* approached 0, which was 0.333. *S* was 11,969.8 km², which is smaller than the previous rain cluster. The long and short axis of the rain cluster were very different and the

shape parameter *WL* was relatively small, so the rain cluster was elongated. The central latitude and longitude of the rain cluster were (109.50°E, 18.20°N) and it was located above the ocean and was therefore an oceanic rain cluster. The mean and maximum rain intensity of the rain cluster were 1.62 and 8.66 mm/h, respectively.

Parameter	Meaning	
<i>S</i> (km ²)	Rain cluster area: the area of a single pixel \times the number of pixels	
<i>L</i> (km)	Length of the long axis of the MBR	
W (km)	Length of the short axis of the MBR	
Angle (°)	Rotation angle of the long axis of the MBR; true north is 0° and clockwise is positive	
WL	Shape of the rain cluster: $WL = W/L$	
Longitude (°E)	Central longitude of the rain cluster	
Latitude (°N)	Central latitude of the rain cluster	
Mean rain rate (mm/h)	Arithmetic mean of the rain intensity in all pixels in the rain cluster	
Maximum rain rate (mm/h)	Maximum value of the rain intensity of all pixels in the rain cluster	
	S (km ²) L (km) W (km) Angle (°) WL Longitude (°E) Latitude (°N) Mean rain rate (mm/h) Maximum rain rate (mm/h)	





Figure 2. Rain intensity of the two rain clusters (units: mm/h). The formation times were (**a**) 16:00 on 27 August 2006 and (**b**) 12:30 on 12 August 2000 (Beijing Time, UTC + 8). The blue rectangle is the MBR; the red solid line is the outline of the rain cluster; the star is the center of the bounding rectangle; and the black solid line is the coastline of Hainan Island.

Table 2. Morphological and physical parameters of the two rain clusters shown in Figure 2.

Morphological Parameters		Physical Parameters	
Parameter	Value (Cluster 1/Cluster 2)	Parameter	Value (Cluster 1/Cluster 2)
<i>S</i> (km ²)	14,437.8/11,969.8	Longitude (°E)	109.67/109.50
L(km)	154.58/199.98	Latitude (°N)	18.80/18.20
W (km)	144.04/66.66	Mean rain rate (mm/h)	3.52/1.62
Angle (°) WL	108.44/90 0.932/0.333	Maximum rain rate (mm/h)	16.22/8.66

3. Results

3.1. Basic Characteristics of the Rain Cluster Morphology and Rain Intensity

The parameters of the 231,664 mesoscale rain clusters were counted and the probability density function (PDF) distributions of various parameters of the oceanic and continental rain clusters were calculated (Figure 3). The PDFs of the areas of oceanic and continental rain clusters first increased, and then decreased with increasing values of S. The occurrence probability of oceanic rain clusters decreased faster than that of continental rain clusters.

Both types of cluster had maximum values near 1000 km², accounting for 27.9 and 25.9% of the total, respectively. There were slightly more oceanic rain clusters than continental rain clusters. The probability density of oceanic and continental rain clusters with an area <10,000 km² was 99.2% and 97.3%, respectively (Figure 3a), indicating that the area of rain clusters over land was larger than rain clusters over the oceans; this is in agreement with the results of Fu et al. [15] and Nesbitt et al. [23].



Figure 3. PDFs of the parameters of oceanic and continental rain clusters: (**a**) *S*, (**b**) length, (**c**) rotation angle, (**d**) *WL*, (**e**) mean rain rate and (**f**) maximum rain rate. The red dotted and blue solid lines represent continental and oceanic rain clusters, respectively.

In terms of the probability–density distribution of the long axis (Figure 3b) for rain clusters <56 km, there were more oceanic rain clusters than continental rain clusters.

Continental rain clusters dominated with an increase in the parameters; oceanic rain clusters with a long axis >100 km accounted for about 9% and continental rain clusters accounted for about 14%.

The rotation angles of the oceanic and continental rain clusters were almost the same (Figure 3c). The three ranges of 40–50°, 90–100° and 130–140° had a high probability of occurrence, accounting for about 26%, 17% and 8% of the clusters, respectively, which together accounted for 51% of the total number of rain clusters. The number of rain clusters was relatively scattered in other directions, indicating that these three directions were characteristic of the long axis of the rain clusters over Hainan Island. The number of rain clusters was largest near a rotation angle of 45°. Oceanic rain clusters occurred more frequently than continental rain clusters in the range WL < 0.5 (Figure 3d), accounting for 51.2% and 42.6%, respectively, and continental rain clusters accounted for a greater proportion at larger sizes.

For long strip (WL < 0.4) and square (WL > 0.8) rain clusters, the proportions of oceanic rain clusters were 31.8% and 20.7%, respectively, and the proportions of continental rain clusters were 25.3% and 23.9%, respectively, indicating that the oceanic rain clusters tended to be more elongated and the continental rain clusters were squarer, in agreement with Liu et al. [24]. In general, the occurrence probability of a long-strip rain cluster was higher than that of a square rain cluster for both oceanic and continental rain clusters.

Cetrone et al. [46] found that most of the radar echo areas on the tropical island of Kwajalein were <300 km², whereas we found that the largest number of rain clusters were about 1000 km² in area. The angle of the radar echoes measured by Cetrone et al. [46] had two peaks around 45 and 135°, consistent with our conclusions, although we found that rain clusters were more likely to occur in an east–west direction.

The PDF distributions of the mean and maximum rain rates of the oceanic and continental rain clusters were similar. As the parameters increased, the oceanic rain clusters peaked before the continental rain clusters and both decreased rapidly (Figure 3e,f). The mean and maximum rain rates showed a similar pattern in the area, long axis and other parameters. The two PDF curves intersected near 0.5 and 1 mm/h, respectively. The probability of oceanic rain clusters was greater before the intersection point, whereas continental rain clusters accounted for a greater proportion after the intersection point. The mean rain-rate peaks of the oceanic and continental rain clusters appeared at about 0.25 and 0.4 mm/h, respectively, and the corresponding proportional probabilities were 23% and 17.3%, respectively. The maximum rain-rate peaks appeared at about 0.63 and 1 mm/h, respectively, accounting for 14.2% and 12.8%, respectively. For rain clusters with a maximum rain rate >8 mm/h, the proportion of oceanic rain clusters was only about one third of that of the continental rain clusters, indicating that more rainstorms occurred over land and more light rain occurred over the ocean, mainly as a result of stronger heating over land. Convective clouds mostly appeared over land, whereas more stratocumulus clouds, with shallower precipitation, appeared over the ocean [47,48].

The distribution of the contribution of the parameters of different-sized rain clusters to precipitation was calculated by binning. Figure 4 shows the contributions of different parameters of oceanic and continental rain clusters, to the total precipitation. Large rain clusters contributed the most to precipitation for both continental and oceanic rain clusters. Large rain clusters over land contributed more to the total precipitation (Figure 4a,b).

The contribution probability of the rotation angle was clearer in the ranges 40-50 and $90-100^{\circ}$ (Figure 4c). The PDF distributions show that most rain clusters had a rotation angle close to 45° , but their contribution to the total precipitation was less than that of rain clusters with a rotation angle close to 90° , indicating that the intensity or area of rain clusters was greater in an east-west direction. *WL* made a greater contribution to precipitation in the range 0.4–0.8 and around 1 (Figure 4d), indicating that long-strip rain clusters contributed less precipitation, but made a higher contribution to oceanic rain clusters than continental rain clusters.



Figure 4. PDFs of the parameters of oceanic and continental rain clusters: (**a**) S, (**b**) length, (**c**) rotation angle, (**d**) WL, (**e**) mean rain rate and (**f**) maximum rain rate. The red dotted and blue solid lines represent continental and oceanic rain clusters, respectively.

With an increase in the rain rate, the contribution of a rain cluster's rain rate to precipitation first increased and then rapidly decreased (Figure 4e,f). The rain rate of the rain cluster was relatively large, but the contribution to precipitation was relatively low. The contribution to precipitation of the mean and maximum rain rates had peaks around 2.5 and 15 mm/h, respectively. The peaks of the mean and maximum rain rates of oceanic rain clusters were earlier than those of continental rain clusters. The peak value of the contribution to precipitation was higher for continental rain clusters.

Figure 5 shows the spatial distribution of rain cluster parameters. Rain clusters with a larger area and longer long axis were concentrated on the northern side of the mountains of Hainan Island (Figure 5a,b). The rain rate was larger on the northern and eastern sides of the mountains (Figure 5e,f). The rain clusters with the largest mean rain rate appeared

in the northeast of Hainan Island, whereas the rain clusters with a larger maximum rain rate mostly appeared on the northern side of the mountains. The spatial distribution of the rain rate, especially the maximum rain rate, is relatively close to that of the area and long axis. Both the area and long axis have potentially close links with the rain rate of rain clusters, especially with the maximum rain rate.



Figure 5. Spatial distribution of parameters of the rain clusters: (**a**) *S*, (**b**) length, (**c**) rotation angle, (**d**) *WL*, (**e**) mean rain rate and (**f**) maximum rain rate.

The heavy rainfall on the northern side of the mountains is mainly attributed to the high frequency of sea and land breezes on Hainan Island [37]. When vigorous sea breezes develop, sea breeze fronts are formed [49–51] and the frontal updraft leads to "sea breeze precipitation" [52,53]. During the day, coastal sea breezes converged strongly in the northeast of the island and precipitation mainly occurred to the west of the island's long axis. This is because precipitation mostly occurred from April to October when the background wind was dominated by the southeastern summer monsoon, which increased the temperature difference between the two sides of the sea-breeze front on the western side of the island's long axis [29]. The sea breeze front in the west was stronger than that in the east [54], which resulted in a greater intensity of precipitation.

The mountainous topography of the southern part of the island divides the southern sea breeze into three parts, forming a cross-mountain airflow and a left–right circulation. The warm and humid airflow is forced upward by the terrain or by convergence [55]. Precipitation therefore mainly occurs on the southwestern and southeastern sides of the mountains. Over the ocean, the intensity of precipitation is lowest in the northwest, with the lowest mean and maximum rain rates.

The rotation angle is greatest on the northeastern side of Hainan Island and in the southwestern coastal areas (Figure 5c). The rain clusters are squarer over land (Figure 5d). As the distance from the island increases, the shape of the rain clusters first becomes elongated and then square. As a result of the unique coastal boundaries, the coastal areas are prone to form linear convective systems, such as mesoscale convergence lines [56,57]. Therefore, the shape of rain clusters in coastal areas is mostly elongated.

3.2. Temporal Variation of Rain Cluster Shape and Rain Rate

We also studied the diurnal variation of the parameters of the oceanic and continental rain clusters (Figure 6). The diurnal variation of the areas of continental rain clusters showed clear changes, with the minimum area occurring at 02:00. The area gradually increased after 11:00 and reached a maximum of 3600 km² at 18:00 (Figure 6a). By contrast, there was no clear change in the diurnal variation of the area of rain clusters over the ocean. The maximum area of 2200 km² occurred at 19:00.



Figure 6. Diurnal variation of the parameters of oceanic and continental rain clusters: (**a**) *S*, (**b**) length, (**c**) rotation angle, (**d**) *WL*, (**e**) mean rain rate and (**f**) maximum rain rate. The red dotted and blue solid lines represent continental and oceanic rain clusters, respectively (Beijing Time, UTC + 8).

The long axis of the continental rain clusters increased after a minimum at 11:00 and reached a maximum of about 70 km at 18:00 (Figure 6b). There was a sub-peak from 02:00

to 05:00. The long axis of the oceanic rain clusters peaked at about 57 km at 02:00 and 21:00 and the minimum of the long axis (about 51 km) appeared at 12:00.

There were clear diurnal variations in the rotation angle of the oceanic rain clusters, with an amplitude close to 6° , whereas the amplitude for continental rain clusters was $<4^{\circ}$ (Figure 6c). The rotation angle of both continental and oceanic rain clusters increased at about 03:00, 10:00 and 18:00. Continental rain clusters maintained a small vibration for several hours at this angle and rainfall increased significantly in these three time periods. The increase in rainfall may therefore be related to the increase in the rotation angle or the more eastward location of the rain cluster.

The shape of the continental rain clusters changed more obviously than that of oceanic rain clusters (Figure 6d). The minimum value of *WL* for the continental clusters was about 0.53 at 02:00. At this time, the rain clusters were relatively slender and then gradually changed to a square. The maximum value of 0.66 appeared at 16:00. The minimum value of the oceanic rain clusters was 0.54 at 02:00 and 22:00 and the maximum value of 0.61 occurred at 12:00.

The variation trend of the mean rain rate of oceanic and continental rain clusters was similar (Figure 6e). The mean rain rate of continental rain clusters changed more than that of oceanic rain clusters during the day and exceeded the mean rain rate of oceanic rain clusters. There were multiple peaks at 02:00, 14:00 and 18:00. The mean rainfall rate of continental rain clusters showed an extra peak in precipitation around dusk. The maximum rainfall occurred at 14:00, when the mean rain rate of continental rain clusters reached about 1.6 mm/h, twice that of oceanic rain clusters. The trends in the diurnal variation of the maximum rain rate of both types of cluster were similar (Figure 6f), but the diurnal variation and intensity of the precipitation of continental rain clusters were greater than those of oceanic rain clusters. The maximum rain rates of 6.4 and 2.6 mm/h for continental and oceanic rain clusters, respectively, occurred at 14:00.

Many researchers have found that night-time rainfall is very common on tropical islands and that this is closely related to inertial oscillations [28]. Chen and Du et al. [58–60] showed that the enhancement of the oceanic boundary layer jets at night triggers convection and, combined with the influence of terrain and cold pools, produces strong rainfall. The peak precipitation in the afternoon is attributed to strong convection caused by solar heating and the peak at dusk is attributed to the strong low-level convergence produced by sea and land breezes around 18:00 [1].

By combining rain intensity, shape and area, we found that the rain intensity reached a peak first, and then the shape reached a peak, followed by a peak in the area of the rain cluster. This shows that the initial convection was triggered by strong heating. The shape was relatively random at the start and the system gradually became more organized. The shape of the precipitation system became square. Under the influence of water-vapor transport, it spread to the surroundings and the area of stratus clouds expanded.

We classified the diurnal variations of the parameters for each month to show the diurnal and intra-annual variations (Figures 7 and 8). The parameters of the oceanic and continental rain clusters were calculated to show the diurnal variation in each month. The area of continental rain clusters showed clear intra-annual and diurnal variations (Figure 7b), mainly concentrated between 13:00 and 21:00 from April–October when the area was relatively large; the area reached a maximum in May. This is because the summer monsoon breaks out in this time period [8]. The area increased again in August as a result of the impact of the later flood season [57]. The area of the continental rain clusters was small in winter, whereas the area of the oceanic rain clusters did not change significantly throughout the year and the rain clusters were always relatively small (Figure 7a).

The long axis of the continental rain clusters also showed significant intra-annual variations (Figure 7d). The long axis was relatively large between 14:00 and 21:00 from April– September and reached a maximum around dusk from April–September. The long axis of continental rain clusters was relatively small in winter with a minimum at 03:00 in January, whereas the oceanic rain clusters had a larger long axis in winter, especially in January (Figure 7c). Dai [61] indicated that the showery precipitation over the ocean peaks in winter while this precipitation over the land peaks in summer, which is ascribable to the differential surface-temperature responses of the ocean and the land. In winter, the ocean cools more slowly and is warmer than the land and, in summer, the ocean heats up more slowly than the land. The convergence of surface winds, which mostly occur over the warm surface, similarly have seasonal variations. It is consistent with the findings of Dai and Deser [62]—that is, showery precipitation is closely related to the convergence of surface winds.



Figure 7. Intra-annual variations in the parameters of oceanic and continental rain clusters: (**a**,**b**) *S*, (**c**,**d**) length, (**e**,**f**) rotation angle and (**g**,**h**) *WL*. The left-hand columns show the parameters of oceanic rain clusters and the right-hand columns show the parameters of continental rain clusters (Beijing Time, UTC + 8).



Figure 8. Intra-annual variations in the parameters of oceanic and continental rain clusters: (a,b) mean rain rate and (c,d) maximum rain rate. The left-hand columns show the parameters of oceanic rain clusters and the right-hand columns show the parameters of continental rain clusters (Beijing Time, UTC + 8).

The rotation angle of oceanic rain clusters was small from December to March, but relatively large at other times. The intra-annual variation of the continental rain clusters was less clear. The rotation angles were close to due east and relatively large throughout the year, with a maximum at 09:00 in January and 21:00 in February (Figure 7e,f).

The *WL* value of oceanic rain clusters was larger between 8:00 and 19:00 from June– October; the oceanic rain clusters were nearly square at these times. The *WL* value of continental rain clusters was >0.66 between 15:00 and 17:00 from April–October (Figure 7g,h).

The mean and maximum rain rates of the continental rain clusters had clearer characteristics than the oceanic rain clusters. The mean rain rate of the continental rain clusters was relatively large throughout the day from November to February, whereas the rainfall intensity was greater from 13:00 to 18:00 from March–May and in October. It was concentrated in the two hours after 12:00 from June–August (Figure 8b). The oceanic rain clusters had similar characteristics, but the magnitude of change was less clear (Figure 8a). This is similar to the observations of Fairman et al. [63] in Great Britain and Ireland. The maximum rain rate on land showed that there was heavier precipitation throughout the day from November–February, whereas heavier rainfall mainly occurred between 13:00 and 19:00 from March–October. The rainfall in the oceanic rain clusters was concentrated between 13:00 to 19:00 from March–October and was relatively large, but still significantly smaller than the continental rain clusters at this time (Figure 8c,d).

The increase in spring rainfall is possibly associated with the latent heat flux peak in the afternoon before the onset of the South China Sea summer monsoon [64]. Li et al. [65] indicated that the diurnal variation of latent heat flux corresponds well with that of precipitation. The increase in latent heat flux means that more water vapor transported into the atmosphere increases the atmospheric instability and likely leads to stronger rainfall intensity. In summer and autumn, the heavy rainfall is closely related to the summer

monsoon and tropical cyclones. In summary, the rainfall in the continental rain clusters was higher throughout the day, even in winter. Rainfall was concentrated from 13:00–18:00 in spring and autumn. In summer, the mean rain rate was relatively strong in the two hours after 12:00 and from March–November the maximum rain rate peaked in the afternoon.

3.3. Relationship between the Morphology of Rain Clusters and Rainfall Intensity

We arranged the meso- β -scale rain clusters in ascending order of parameters, divided the samples into 100 groups, calculated the average of each group and obtained 100 sample points. We then found the relationship between the morphological parameters of the rain clusters and the mean and maximum rain rates corresponding to the 100 sample points. Grouping of equal samples can reduce the influence of extreme values in the original data and has the power of a statistical test.

The relationship between the parameters of the oceanic and continental rain clusters and the rain intensity are shown in Figures 9 and 10, respectively. There was a clear positive correlation between the area, long axis and rain rate of the rain clusters at the 95% significance level but there was a significant difference between the oceanic and continental values. The correlation coefficient between the parameters of the continental rain clusters and the rain rate was higher than the correlation coefficient for the oceanic rain clusters. This showed that, as the area of the rain cluster increased, the intensity of rainfall over land increased more than that over the ocean.



Figure 9. Relationship between the parameters of oceanic and continental rain clusters and the rain intensity: (**a**) *S* and the mean rain rate, (**b**) *S* and the maximum rain rate, (**c**) length and the mean rain rate and (**d**) length and the maximum rain rate. The blue and red lines represent the regression line of oceanic and continental rain clusters, respectively, and the blue- and red-shaded areas represent the 95% prediction intervals of oceanic and continental rain clusters, respectively. R2_O and F_O represent the *R*² and *F* values of the oceanic regression line; R2_L and F_L are the *R*² and *F* values of the continental regression line.



Figure 10. Relationship between the parameters of oceanic and continental rain clusters and the rain intensity: (**a**) rotation angle and the mean rain rate, (**b**) rotation angle and the maximum rain rate, (**c**) *WL* and the mean rain rate and (**d**) *WL* and the maximum rain rate. The blue and red lines represent the regression line of oceanic and continental rain clusters, respectively, and the blue- and red-shaded areas represent the 95% prediction intervals of oceanic and continental rain clusters, respectively. R2_O and F_O represent the *R*² and *F* values of the oceanic regression line; R2_L and F_L are the *R*² and *F* values of the continental regression line.

The two most significant relationships were between the area and the long axis of the continental rain clusters and the maximum rain rate (Figure 9b,d). The maximum rain rate could be characterized by describing the area and long axis of the rain cluster. There was no significant linear relationship between the rotation angle of the oceanic and continental rain clusters and the rain rate (Figure 10a,b) so the rotation angle was not sufficient to describe the rain rate. The positive correlation between the *WL* value of the oceanic rain clusters and the rain rate was stronger than that of the continental rain clusters (Figure 10c,d), especially the positive correlation between the *WL* value of the oceanic rain clusters and the maximum rate, indicating that the squarer the ocean rain cluster, the stronger the rainfall intensity. The shape parameter can therefore describe the maximum rain rate of the rain cluster.

4. Conclusions

We first binarized the satellite image, and then used the connected area recognition technology of OpenCV to identify all the meso- β -scale rain clusters that appeared over Hainan Island and the surrounding areas between 1 June 2000 and 31 December 2018 from GPM IMERG satellite precipitation data. We defined the parameters of the rain clusters based on the minimum-bounding rectangle-fitting method and topographic data and then

carried out a statistical analysis on the parameters to explore the characteristics of the rain clusters and the relationship between the parameters and the rain rate. Our main conclusions are as follows:

- 1. From the probability density distribution of rain clusters, the area of most mesoscale rain clusters was <10,000 km² and the area and long axis of the continental rain clusters were larger than those of the oceanic rain clusters. The oceanic and continental rain clusters had three characteristic directions: 40-50°, 90-100° and 130-140°. More rainstorms occurred over land and there was more light rain over the ocean. In terms of the contribution to precipitation, large rain clusters or rain clusters in an east-west direction contributed the most to precipitation for both oceanic and continental rain clusters; long-strip rain clusters or rain clusters with a strong rainfall intensity contributed less to precipitation. In terms of the spatial distribution of their parameters, rain clusters with a large area or a long axis were concentrated on the northern side of the mountains of Hainan Island and the rain rate was larger on the northern and eastern sides of the mountains. The rotation angle was greater on the northeastern side of Hainan Island and in the southwestern coastal areas. The rain clusters over land were square and the rain clusters over coastal areas were elongated. In general, the occurrence probability of elongated rain clusters was higher than that of square rain clusters;
- 2. The variation over time of the parameters of rain clusters was significant and the changes were more dramatic in continental rain clusters. The area and long axis of rain clusters were relatively large between 14:00 and 21:00 from April–September and were smaller in winter. The area of oceanic rain clusters was relatively small throughout the year, but the long axis increased in winter. The maximum shape value of 0.66 appeared at 16:00 for continental rain clusters, whereas the maximum value of 0.61 for oceanic rain clusters appeared at 12:00. Continental rain clusters were nearly square for a longer time than oceanic rain clusters. The diurnal and intra-annual variations of the rotation angle of oceanic rain clusters were greater than those of continental rain clusters. The rotation angle of oceanic rain clusters was smaller from December-March. In addition, the rainfall in continental rain clusters was relatively even in winter and precipitation occurred in the early morning. In spring and autumn, precipitation mainly occurred in the afternoon and, in summer, precipitation was concentrated in the two hours after 12:00. The oceanic rain clusters had similar characteristics. Both the oceanic and continental rain clusters had large maximum rain rates in the afternoon from March-October;
- 3. There was a clear positive correlation between the area, long axis and rain rate of both oceanic and continental rain clusters. The correlations between the area, long axis and rain rate of continental rain clusters were higher than those for the oceanic rain clusters; as the area or the long axis increased, the rainfall intensity over land was higher than that over the ocean. The correlation between the morphological parameters of the rain clusters and the maximum rain rate was higher than the correlation with the mean rain rate. The maximum rain rate of the rain clusters can therefore be characterized by describing the area, long axis and shape of a rain cluster.

The key finding of this study was to quantitatively obtain the morphology, rainfall intensity and their relationship from the perspective of the rain cluster. The use of morphological parameters such as the area, scale and shape of the rain cluster has the potential to predict precipitation over Hainan Island and the surrounding areas. This will help to improve the accuracy of the geostationary satellite infrared algorithm used to estimate precipitation. We also found that there are diurnal and monthly changes in the morphology and rainfall intensity of rain clusters and there may be some transfer process between them. Future research will consider time as a variable and the adaptive Kalman filter method will be used to obtain more accurate estimates of precipitation. **Author Contributions:** Conceptualization, T.H. and Y.C.; methodology, T.H. and Y.C.; software, T.H.; validation, T.H. and Y.C.; formal analysis, T.H.; investigation, T.H.; resources, T.H. and Y.C.; data curation, T.H.; writing—original draft preparation, T.H.; writing—review and editing, T.H. and Y.C.; visualization, T.H.; supervision, Y.C. and W.L.; project administration, Y.C. and C.D.; funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

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