Land–Sea Contrast in the Diurnal Variation of Precipitation from Landfalling Tropical Cyclones

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Abstract Recent composite analysis of landfalling tropical cyclones (TCs) suggests a rain rate peak in the early morning, which contradicts the typically observed peak in convective precipitation over land seen in the late afternoon to early evening. We conducted a set of idealized simulations of TCs and analyzed observational data from TC Bebinca (2018), which stalled near the shoreline of southern China. We show a distinct land–sea contrast in the diurnal variation of TC precipitation and an 8–12 hr offset between the peak precipitation time over land compared with that over the sea in a TC that stalls at the shoreline. The highest land surface temperature and maximum low-level buoyancy during the afternoon led to peak precipitation over land at this time. However, the peak precipitation over the sea in the early morning was generated by the increase in relative humidity caused by nighttime radiative cooling and enhanced instability.

Plain Language Summary Heavy rainfall associated with tropical cyclones (TCs) causes great economic loss and fatalities in coastal and inland regions worldwide. Do TCs show predictable diurnal fluctuations in rainfall, which can be valuable information for TC flooding risk or water resource management? The diurnal cycle in TC cloudiness over oceans might provide clues to this problem. Recent studies suggest an early morning peak in TC rainfall over land and sea, which seems to contradict the late afternoon to early evening peak observed over land for shower and thunderstorm activity unrelated to TCs. We found that for a TC stalled at the shoreline, peak rainfall over land lags that over sea by 8–12 hr, although the peak rainfall over sea still occurs in the early morning. Our results show, that for a landfalling TC, the offset in peak rainfall time between land and sea stems from the influence of land–sea thermal and roughness contrasts on the atmosphere.

1. Introduction

Tropical cyclones (TCs) and the associated heavy rainfall are among the costliest natural hazards to impact both coastal and inland communities. For example, landfalling Hurricane Harvey (2017) poured more than 1,300 mm of rainfall over and around the heavily populated Houston area, causing at least 68 fatalities and economic losses of 125 billion dollars (Blake & Zelinsky, 2018; Emanuel, 2017; Zhang, 2018). It is therefore essential that we are able to accurately forecast TC rainfall both in terms of timing and intensity. A number of observational studies have already found a clear diurnal cycle in the coverage and maximum height of canopy clouds around TCs (Browner et al., 1977; Dunion et al., 2014; Knaff et al., 2019; Kossin, 2002; Lajoie & Butterworth, 1984; Leppert & Cecil, 2016; Muramatsu, 1983; Steranka et al., 1984; Wu & Ruan, 2015). The diurnal cycle is one potentially predictable and important component of TC precipitation variability.

Although some studies have examined the diurnal cycle of TC rainfall over the oceans (e.g., Bowman & Fowler, 2015; Jiang et al., 2011; Leppert & Cecil, 2016; Wu et al., 2016) and have found a predominant nocturnal or early morning rainfall peak, the diurnal cycle of TC precipitation has yet to be fully explored. This is especially true for TCs that are close to sizable landmasses, and there is some disagreement among the observational studies regarding such details as whether there is a single diurnal peak or two peaks and the timing of precipitation maxima (Bowman & Fowler, 2015; Dunion et al., 2014; Frank, 1977; Jiang et al., 2011; Matyas, 2013). Several mechanisms have been proposed to explain the TC diurnal cycle, which is ultimately attributed to radiative impacts including cloud–radiation interaction (Melhauser & Zhang, 2014; Tang et al., 2017, 2016; Tang & Zhang, 2019). Large differences exist in the diurnal variations seen in global precipitation...
between the open oceans and the continents (Dai, 2001). The convective precipitation over land is considered to be a direct response to daytime heating of the surface and the planetary boundary layer and tends to peak in the late afternoon to early evening when convective available potential energy in the atmosphere reaches its maximum during summer (Dai, 2001). Land surfaces have the potential to influence the diurnal cycle of TC precipitation, and these effects have been investigated using limited observational and modeling studies (Bowman & Fowler, 2015; Hu et al., 2017; Jiang et al., 2011; Tuleya, 1994). However, there is a divergence of views (Hu et al., 2017; Jiang et al., 2011), and how the land impacts the phase and amplitude of the diurnal precipitation cycle of a landfalling TC remains to be determined. Although moisture supply is thought to be the dominant factor in the asymmetric distribution of convection associated with a TC making landfall (Chan & Liang, 2003), in addition to the influence of TC motion and vertical wind shear (Chan et al., 2004), the factors and processes controlling the diurnal variation of such convective asymmetry require further investigation, especially for TCs that stall near the shoreline.

In this paper, we investigate the differences in the diurnal variations of precipitation over land and sea within the primary circulation region of a landfalling TC and attempt to identify the underlying mechanism driving these land–sea contrasts. We also determine the impact of cloud–radiation feedback on the diurnal cycle of a landfalling TC. We hypothesize that the contrasting dynamical and thermodynamical properties of land and sea surfaces are the main source of the large differences in the diurnal variations of convection and precipitation, although the interaction between the strong swirl circulation of a TC and the diurnal cycle of sea–land breezes influences the land–sea contrast seen in diurnal variations of precipitation.

In the real world, the spatiotemporal rainfall distribution of a landfalling TC is controlled jointly by many environmental factors besides the land–sea contrast. Idealized case studies make it easy to isolate the influence of the land–sea contrast from other factors, such as vertical wind shear and storm motion. Consequently, a base experiment with a TC located directly over a north–south oriented straight coastline (hereafter SHORE case) was designed on an f plane in a quiescent environment. For comparison, we also performed two more experiments with sea-only (OCEAN) and land-only (LAND) surfaces. We expect that the TC diurnal precipitation cycle will differ over the sea and land areas of the SHORE experiment, as it will in the OCEAN and LAND experiments during the quasi-steady period. We also used observational data from a recent and typical real-world TC (i.e., Typhoon Bebinca in 2018), which is similar to the setting of SHORE case, to verify that the results of the idealized simulations were reasonable and have implications for operational TC forecasting.

2. Study Methods

We used the Cloud Model 1 (Bryan & Rotunno, 2009) to simulate the idealized TCs. The domain size was 2,900 km in both horizontal directions. The resolution was 4 km in the central area of 1,000 km, and the grid outside was stretched to maximum spacing of 16 km. The vertical grid had 55 levels with a resolution of 50 m under 0.1 km and a grid spacing gradually increasing to 600 m above 7.9 km. The Coriolis parameter was set to the value at 20°N throughout the domain. The environment was horizontally uniform and quiescent with a moist tropical sounding as in Dunion (2011). The initial structure of the TC had an approximate maximum 10-m-level wind speed of 29 m·s⁻¹ at a radius of 52 km (Figure S1), which is similar to the conditions used in Rotunno and Emanuel (1987). We used the radiation scheme from the rapid radiative transfer model for general circulation models (Iacono et al., 2008). Yonsei University boundary layer parameterization scheme (Hong et al., 2006) was used. A revised version of the Advanced Weather Research and Forecast model similarity theory code was used for the surface layer (Jiménez et al., 2012).

The control experiment (SHORE) was run using a straight north–south oriented coastline at the center of the domain, with land to the west and the sea to the east. An imposed sea surface temperature of 301 K was kept constant, which is reasonable under the conditions of high wind and dense cloud cover associated with TCs (Gentemann et al., 2003). The land surface temperature varied with time. The TC’s center was always kept at the coastline with very small and slow wobbles. The two comparative experiments were based on SHORE with the following perturbations: ocean-only (OCEAN) and land-only (LAND) surfaces across the whole domain. The analyzed outputs from the three experiments all covered the integration time of 121–216 hr, the period when precipitation showed an obvious diurnal oscillation (Figures S2c and S2d). These several days of data were then composited to form just a single diurnal cycle. We then calculated the rain rate
anomaly percentage as follows: the rain rate at each time minus the average over the integration time of 121–216 hr divided by the average.

Another idealized simulation is also performed to assess the sensitivity of land–sea contrast in the diurnal variation of TC precipitation to TCs’ translation speeds towards the coastline. The experiment was based on SHORE except that the coastline was set at about 1,209-km west of TC center from the start of model integration (i.e., 48 hr for MS7 experiment in Figure S2). The coastline was then moved perpendicularly towards the TC from west to east with a speed of 7 m·s\(^{-1}\) in the model domain. The directions here did not have much physical meaning since all experiments were performed on an \(f\) plane. This strategy was already used in previous studies (e.g., Chan & Liang, 2003; Tuleya & Kurihara, 1978) to avoid any complication involving a steering current. Although the effect of asymmetries arising from the superposition of a steering current onto a TC vortex cannot be simulated, the lack of such asymmetries should be desirable here, since the objective is to examine the response to the changes in the underlying surface from sea to land. In addition, the conclusions will be insensitive to TC’s moving parallel to coastline in this framework of idealized simulations.

3. Data

To verify the findings from our idealized simulations, we analyzed observational data from TC Bebinca (2018). The best track data from the website of the China Meteorological Agency (Ying et al., 2014) were used to obtain TC positions and maximum wind speeds. RSMC best track data from Japan Meteorological Agency were also used to estimate its size. We used version 05 of the IMERG (Integrated Multi-satellite Precipitation Mission) Final Precipitation L3 dataset (GPM_3IMERG), which is half-hourly at a resolution of 0.1° (Huffman, 2017). NCEP Reanalysis data, which are 6-hourly at a horizontal resolution of 2.5° (Kalnay et al., 1996), were used to calculate the vertical shear of the large-scale winds. ERA-Interim data, which are 6-hourly at a horizontal resolution of 0.125° (Dee et al., 2011), were used to calculate surface temperature of sea and land for the TC Bebinca (2018).

4. Results of the Idealized Simulations

4.1. The Control and Comparative Experiments

Figure 1 shows the diurnal variation of the precipitation anomaly percentage in the SHORE (Figures 1e–1h) and also in the two comparative experiments, OCEAN (Figures 1a and 1b) and LAND (Figures 1c and 1d). The outer size (indicated by the radius where 10-m tangential wind speeds equal 8 m·s\(^{-1}\) [c.f., Schenkel et al., 2018]) of these simulated TCs is about 330 km. The 400-km radius criterion is based on the typical radius of the TC primary wind circulation (80–400-km radius from the TC center; Prat & Nelson, 2013). The OCEAN experiment shows similar results to those reported in previous studies (Bowman & Fowler, 2015); that is, maximum precipitation occurs around early morning or midnight in both the TC primary circulation region and outer region (Figures 1a and 1b). In comparison, the maximum precipitation occurs during the early afternoon in the LAND experiment. The 24-hr harmonic of precipitation is nearly out-of-phase between the LAND and OCEAN experiments. We focused on the diurnal precipitation variation over land and sea in the SHORE experiment. The timing of precipitation over the sea was essentially the same as in the OCEAN experiment, except with a small lag in the outer region (Figures 1e and 1f); however, the amplitude of the 24-hr harmonic was much larger than in the OCEAN experiment. Over land, the amplitude of the 24-hr harmonic was only a little smaller than in the LAND experiment, and the timing in the outer region had a small lag relative to that of the LAND experiment (Figures 1g and 1h). There were double peaks in precipitation outside a radius of 400 km over the land in the SHORE experiment (Figure 1h), which is consistent with observations (Jiang et al., 2011). Our results reveal that the diurnal precipitation cycles over land and sea become nearly out-of-phase when a TC stalls at the shoreline. The comparison from the snapshots of column maximum vertical motion and precipitation rate at key times also support the above statements further (Figure 2).

In the SHORE experiment, to investigate the underlying mechanism that leads to the land–sea contrast in the diurnal variation of precipitation (Figure 2), the vertical structures of the TCs were analyzed at the time of maximum and minimum precipitation over land and sea (Figure 3). The maximum precipitation over the land occurs at about 1500 LST (local solar time; Figures 1g and 1h). The total mixing ratio of rainwater, snow, and graupel/hail was much greater at 1,500 than 2300 LST. The cloud water/ice mixing ratio was...
also greater outside of 200 km at 1500 LST (Figures 3a and 3b). We attribute this to the stronger updraft of the eyewall and low-level upward motion outside the eyewall at 1500 LST compared with 2300 LST (Figures 3e and 3f). The stronger upper-level outflow also leads to an increased outward extension of the high cloud canopy (Figures 3a and 3e). The widely extended mid-level downward motion suppressed convection and

Figure 1. Diurnal variation of rain rate percentage anomaly (%) within a radius of 0–400 km (a, c, e, and g) and 400–800 km (b, d, f, and h) for the experiments (a and b) OCEAN, (c and d) LAND, (e and f) over the sea quadrants of SHORE, and (g and h) the land quadrants of SHORE. Red and blue curves indicate the diurnal and semidiurnal harmonics, respectively, and the variance contributions were calculated using all harmonics up to 12.
precipitation at midnight (ca. 2300 LST; Figures 3b and 3f). In contrast, the diurnal precipitation cycle over
the sea was nearly out-of-phase with that over land. In the early morning (ca. 0300 LST), the amplitude of
precipitation was at its maximum, with the strongest eyewall updraft and greatest total mixing ratio of
rainwater, snow, and graupel/hail (Figures 3c and 3g), which is consistent with previous studies of TC
diurnal cycles over the ocean (Bowman & Fowler, 2015; Tang & Zhang, 2019). This is induced mainly by
the enhancement of instability and convection favored by the net radiative cooling that occurs at night
(Melhauser & Zhang, 2014). The minimum precipitation and weakest transverse circulation over the sea
occur in the afternoon (ca. 1500 LST; Figures 3d and 3h).

The following analysis focuses on the radial range of 0–400 km in the SHORE experiment. It will reveal that
the direct (the directly induced diurnal cycle of buoyancy) effects of the diurnal cycle of land surface tem-
perature (Figure S3) on the diurnal precipitation variation are obvious over land. Figure 4c clearly shows
that the low-level (under 1 km) maximum positive buoyancy occurs in the afternoon and is in phase with
maximum precipitation. The vertical gradient of pressure is broadly out-of-phase with the buoyancy

Figure 2. Two-hr-average column maximum vertical motion (left; shading; m·s⁻¹) and precipitation rate (right; shading; 
mm·h⁻¹) at the local time of (a and d) 0300 LST; (b and e) 1500 LST; and (c and f) 2300 LST from the SHORE experiment. 
Purple and brown dashed circles are radii of 400 and 800 km, respectively. Land (sea) is on the left (right) of the brown line.
Figure 3. Radius-height plots of 2-hour-average (a and b) cloud water/ice mixing ratio (contours; 10^{-5} kg·kg^{-1}) and rainwater/snow/graupel/hail mixing ratio (shading; kg·kg^{-1}); (c and d) tangential (black contours; m·s^{-1}), radial (purple contours; every 3 m·s^{-1} from -15 to 15 m·s^{-1}; solid, dashed, and bold denote positive, negative, and zero, respectively) and vertical wind component (shading; m·s^{-1}) for over land quadrants of the SHORE experiment at 1500 and 2300 LST. (c and d) as in (a and b), and (g and h) as in (e and f), but for over the sea quadrants at 0300 and 1500 LST.

Figure 4. Averaged (a and b) radial, tangential, and total divergence (10^{-6} s^{-1}); and (c and d) buoyancy (red; 10^{-2} m·s^{-2}), vertical pressure gradient (purple; 10^{-2} m·s^{-2}), and the sum of both (blue; 10^{-5} m·s^{-2}) under a 1-km height over land quadrants of the SHORE experiment within a radius of (a and c) 0–400 km and (b and d) 400–800 km. Rain rate percentage anomaly (black curves, %) are superimposed in each panel. All time series are filtered to remove scales less than 9.6 hr.
The sum of the buoyancy and the pressure gradient approximates the vertical acceleration, which also reaches its maximum in the afternoon (Figure 4c). Therefore, the land surface heating and buoyancy affect the upward acceleration. Meanwhile, the low-level convergence has an obvious diurnal oscillation (Figure 4a), and the maximum also occurs at nearly the same time as the upward acceleration. We also found that the radial convergence anomaly is the main contributor to the total convergence anomaly (Figure 4a). The amplitude of the tangential convergence oscillation is relatively small (Figure 4a). On the other hand, the maximum precipitation over the sea occurs at night or in the early morning (Figure 1e). Higher relative humidity and instability at night (Figure 5a) over the sea due to net radiative cooling are beneficial to convection and maximum precipitation (Tang & Zhang, 2019), although diurnal cycle of buoyancy is not obvious there (Figure 6c). And stronger updrafts accompany increasing low-level radial inflow and convergence at night (Figures 2a, 3c, and 6a). The radial range of 0–200 km was also checked, and similar conclusions can be drawn (figure not shown).

Figure 5. Averaged relative humidity (solid; %) and lapse rate (−dT/∂z; dashed; 0.1 K·km$^{-1}$) over ocean quadrants for the SHORE experiment within a radius of (a) 0-400 km, (b) 400-800 km at the local time of 0300 LST (blue) and 1500 LST (red).

Figure 6. As Figure 4, but over the sea quadrants in the SHORE experiment.
We analyzed precipitation at a radial range of 400–800 km and compared it with that inside 400 km, because the outer area is thought to be less controlled by TC primary circulation (Prat & Nelson, 2013). The maximum upward motion and precipitation occur at night (afternoon) over sea (land; Figure 2). Despite no obvious diurnal cycle of buoyancy over the sea (Figure 6d), the maximum precipitation occurs in the early morning (Figure 1f). This early morning peak can be explained by nighttime destabilization and humidification (Figure 5b; Melhauser & Zhang, 2014; Tang & Zhang, 2019). The outer area of simulated TC is also influenced by the land–sea breeze, because it is located on the shoreline (Figure 7). The amplitude of cross-shoreline (east–west here) wind component associated with land–sea breeze is always maximum near the shoreline and decreases far away (c.f., Figure 2b of Rotunno, 1983). The total average divergence anomaly is approximately equal to that due to east–west component of the wind only (figure not shown), so the convergence/divergence pattern in Figure 7 results mostly from the land–sea breeze. Consequently, in addition to the favorable conditions of moisture and instability at night, the convergence associated with the land breeze (westerly wind overall) over the sea is also beneficial to convection and maximum precipitation (Figures 6b and 7; c.f. Du & Rotunno, 2018). The maximum precipitation in the afternoon over land is accompanied by the maximum convergence (Figure 4b), which also partially results from the convergence associated with the sea breeze (easterly wind overall; Figure 7). The diurnal variation of radial divergence over land is smaller outside of 400 km than inside (Figures 4a and 4b). However, there is still an obvious diurnal cycle of buoyancy and the vertical pressure gradient over land at a radial range of 400–800 km, as is the case inside 400 km (Figure 4d), and the maximum upward acceleration corresponds to the maximum precipitation in the afternoon (Figures 4d and 1h). Consequently, outside of the TC’s primary circulation, the direct effect of land surface heating acts on the diurnal variation of precipitation over land. The indirect effect generated by the land–sea surface temperature contrast also acts on the diurnal variation of precipitation, both over the land and sea by the low-level convergence associated with the land–sea breeze.

4.2. The Sensitivity to TC Translation Speeds

It was designed that the TC center began to landfall from 96 hr in the MS7 experiment. We focused on the west semicircle of the TC over the land with the radius of 400 km. Figure 8 shows the diurnal variation of rain rate percentage anomaly over the land quadrants after the landfall of TC center during the 24 hr from 96 to 120 hr. In general, the features of diurnal precipitation variation over land are similar to that of the

![Figure 7](image-url)  
**Figure 7.** Time series of average divergence anomaly (shading; $10^{-5}$ s$^{-1}$), east–west wind anomaly (contour; every 0.5 m·s$^{-1}$; solid, dashed, and bold denote westerly, easterly, and zero anomaly, respectively) under 1 km across the shoreline within a radius of 400–800 km from the TC center in the SHORE experiment. All time series are filtered to remove scales less than 9.6 h.

![Figure 8](image-url)  
**Figure 8.** As Figure 1, but for the land quadrants of MS7 experiment.
SHORE experiment in both the TC primary circulation region and outer region (Figures 1g and 1h). Within
the TC primary circulation, the peak rainfall over land still occurs in the afternoon with a small lag behind
that of SHORE. This is because the precipitation maintains its oceanic characteristics for some time as the
TC makes landfall, causing land characteristics to develop later, as is seen in the MS7 experiment.
Instead, the amplitude of the 24-hr harmonic of rainfall over the sea quadrants of MS7 experiment is very
small with variance contributions of ~1%, during the 24 hr before the landfall of TC center for the MS7
experiment (Figure not shown). This may be due to the overwhelming contributions of high-frequency oscil-
lations arising from the rapid approaching land.

In summary, the fast movement of a TC cannot change the basic feature of diurnal precipitation variation
over land after landfall except for a small lag of peak precipitation during the afternoon.

5. Verification Using Observed TC Data

The land–sea contrast seen in the simulated diurnal variation of precipitation was also found in observations
from a real-world TC that made landfall; for example, Typhoon Bebinca (2018) over the South China Sea. We
analyzed the 24-hr period between 0000 UTC August 11 and 0000 UTC August 12, when Bebinca was close
to the shoreline of southern China near about 21°N and moving very slowly parallel to the coastline mostly
(Figure 9a). Its size was estimated between 330–400 km according to the best track data (the available closest

Figure 9. (a) The track of TC Bebinca (2018) (curves with dots denote the position of the TC center every 6 hours from
0000 UTC August 10 to 0000 UTC August 14; red denotes the analysis period). The white circle is centered at the
average position (big black dot) during the analysis period with radii of 400 km. The purple line approximates the
shoreline. The difference of surface temperature between 0600 UTC (1330 LST) and 1800 UTC (0130 LST) August 11
(shading; K). (b) Maximum wind speed (red solid curve), vertical wind shear between 200 and 850 hPa within a radius of
0–400 km (red dotted curve), average precipitation rate within a radius of 0–400 km (red dotted curve), average precipitation rate within a radius of 0–400 km (blue solid curve). (c) Rain-rate percentage anomaly (black curve) over the sea quadrants on 11 August within a radius of 0–400 km with its diurnal (red
curve) and semi-diurnal harmonics (blue curve). (d) as in (c), but for the land quadrants.

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to the shoreline of southern China near about 21°N and moving very slowly parallel to the coastline mostly
(Figure 9a). Its size was estimated between 330–400 km according to the best track data (the available closest
time is 0000 UTC August 13) by using the equation (8) of Dean et al. (2009), which was close to that of SHORE experiment. The intensity of Bebinca was steady, and the vertical wind shear of the environment—the average difference in the wind vector between 200 and 850 hPa within a radius of 400 km from the TC center—was extremely small (less than 5 m·s\(^{-1}\)) and easterly during most of the period analyzed (Figure 9b). The SST nearby remained nearly constant 303 K, while the maximum diurnal variation of land surface temperature is greater than 7 K within the primary circulation of Bebinca during the day analyzed (Figure 9a). These conditions demonstrate some similarity of Bebinca to the SHORE experiment.

The average height of topography over land within 400 km radius is less than 190 m with very small slope (figure not shown). Although a caveat is that the small-scale topography might adjust rainfall distribution locally, the land–sea contrast in the diurnal variation of precipitation over larger area overall would be dominated by land–sea thermal and roughness contrasts as shown in the SHORE experiment.

The diurnal cycle of the precipitation was well developed (Figures 9c and 9d). The maximum precipitation within a radius of 400 km over the sea (land) occurred at 9 (15) LST in the morning (afternoon). The horizontal distribution of rain rate at key times also confirms the land–sea contrast in the diurnal variation of precipitation from Bebinca (Figure 10). These results from Bebinca are essentially consistent with those from the idealized SHORE experiment described above, although some small biases exist that may be related to the complexity of the underlying surface and environment associated with Bebinca. In the real-world case of Bebinca, the interactions of TC with nearby synoptic weather systems may affect the diurnal precipitation cycle in the outer region (outside of 400 km) significantly, where it is not appropriate to compare with the idealized experiment any more.

For other landfalling TC cases, similar features of land–sea contrast in the diurnal variation of precipitation were also found, such as Pabuk (2007; Figure S4).

Figure 10. Rain rate (mm·h\(^{-1}\)) of Bebinca (2018) for (a) 0130 UTC (0900 LST), (b) 0730 UTC (1500 LST), (c) 1330 UTC (2100 LST), (d) 1930 UTC (0300 LST) August 11. The purple circle is centered at the position of the analysis time with radii of 400 km. The blue line approximates the shoreline.
6. Discussion and Conclusions

The diurnal cycle seen in TC precipitation over the open ocean has been well documented (Bowman & Fowler, 2015; Jiang et al., 2011). However, diurnal precipitation variations associated with landfalling TCs have received less attention and remain to be fully understood. In this study, we conducted a set of idealized simulations to investigate whether a land–sea contrast exists in the diurnal variation of precipitation from a landfalling TC and attempted to explain how the different dynamical and thermodynamical properties of the land and sea surfaces affect the amplitudes and phases of the overlying diurnal precipitation cycle.

We found that the diurnal peak in precipitation over the continent (sea) occurs during the afternoon (early morning) for a TC stalled at the shoreline. Precipitation inside a radius of 400 km from the TC center is related mainly to the intensity of the TC eyewall and rainbands. The direct cause of the timing of peak precipitation over land seems to be the maximum surface temperature and low-level buoyancy during the local afternoon. Peak precipitation over the sea occurs in the early morning because of the increasing relative humidity and enhanced instability caused by nighttime radiative cooling (Tang & Zhang, 2019). In the outer region of the TC, the indirect effect generated by the land–sea surface temperature contrast is the low-level convergence associated with the land–sea breeze, which also acts on the diurnal variation of precipitation over the land in company with the direct effect. Moving towards the inner core of the TC, it is more difficult to separate the effect of the land–sea breeze from the stronger TC primary circulation, and the land–sea breeze tends to be weaker relative to the outer region as a result of smaller land–sea surface temperature contrasts. Moreover, the basic features of diurnal precipitation variation over land after landfall of a TC are insensitive to its translation speed. In the composite studies of many real TCs during landfall (e.g., Hu et al., 2017), the peak rainfall over land at early morning may be due to many samples with most of their inner core regions still over sea. This may be because they still retain their oceanic character for a time when the fraction of land within the primary circulation region of TC is small, which was implied by Bowman and Fowler (2015; their Table 6).

This study provides strong support from idealized simulations and observed data of Typhoon Pabuk (2007) and Bebinca (2018) for the hypothesis that the contrasting dynamical and thermodynamical properties of land and sea surfaces will result in the large differences in the diurnal variations of convection and precipitation in the landfalling TCs. It emphasizes the need to realistically parameterize the air–land and air–sea interactions simultaneously and couple with cloud–radiative interactions in the operational forecast models to improve the TC rainfall prediction skill during landfall. We acknowledge that our simulations were idealized; for example, they included no large-scale forcing or interaction with other systems. Further studies will be the larger scale topography effect on the diurnal precipitation cycle from landfalling TCs and the sensitivity of diurnal rainfall variation to the intensity and size of landfalling TCs.

References


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