Rainfall Reinforcement Associated with Landfalling Tropical Cyclones

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ABSTRACT

Landfalling tropical cyclones (TCs) often bring about heavy rainfall, which typically decreases with the weakening of the TCs. However, some TCs may suddenly be reinvigorated after they become remnants over land. Such TCs may produce even stronger rains than those at the time of their landfall. This reinvigorating phenomenon is known as “rainfall reinforcement associated with landfalling tropical cyclones” (RRLTC). The TCs triggering rainfall reinforcement account for 9.7% of the total number of TCs that make landfall on mainland China and often cause problems and surprises for forecasters. The TCs with rainfall reinforcement mostly make landfall in the area of the southeastern coast of China and move primarily along two tracks, spreading northward or westward. RRLTC often occurs in the remnant of a tropical depression that has already been downgraded from typhoon intensity, particularly in a period when the remnant has slowed down or even stagnated. The highest frequency of RRLTC occurrence is during the third day after landfall and in the northeast quadrant of a TC moving northward and the southwest quadrants of a TC moving westward. Diagnostic analysis shows that an RRLTC with a northward track can be mainly attributed to the interaction between westerly troughs and the tropical cyclone. In this way, a remnant gains baroclinic energy from the midlatitude trough. Such an interaction does not appear for northward track TCs without rainfall reinforcement. Rainfall reinforcement for TCs with a westward track is mainly due to the interaction between monsoon surge cloud clusters and tropical cyclones, which is favorable for moisture and latent heat gain. Analyses show that the westward TCs would not have rainfall reinforcement without such an interaction. RRLTC requires new energy transport into TCs. The results of the present study indicate that baroclinic potential energy and latent heat are the two major energy sources that will trigger the remnant revival and rainfall reinforcement. Land surface topography also plays an important role in increasing the rainfall of TCs.

1. Introduction

Observational evidence (Chen 2006; Cheng et al. 2008) has shown that tropical cyclones (TCs) often bring about torrential rains when they make landfall. When a TC weakens into a cloud remnant, rainfall decreases correspondingly. However, in some cases, the remnant will be reviviscent and produce even heavier rainfall than it did at landfall if it has acquired new energy from land. Such

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after it moved inland and was downgraded to a tropical depression (TD). The reinforcement of rainfall from this dissipating typhoon produced a record of extreme precipitation in mainland China with a total of 1062 mm of rainfall in 24 h, which led to the well-known August 1975 (“75 8”) severe flooding, which caused more than 26,000 deaths and economic losses of 10 billion Renminbi yuan (Chen 2010). More recently, the severe Tropical Storm Bilis (0604) (Gao et al. 2009) experienced reinforced rainfall after landfall and resulted in an extremely severe meteorological disaster, causing sustained torrential rains, flooding, debris flow, and mudslides in southern China. The fatalities and economic losses of Bilis (0604) are 843 and 34,829 billion Chinese yuan, respectively (Chen 2010). Therefore, it is vitally important to study RRLTC for improved forecasting and disaster prevention and mitigation.

Over the years, meteorologists (Bosart and Carr 1978; Chen and Ding 1979; Tao et al. 1980; Dimego and Bosart 1982a,b; Mark 1993; Rogers et al. 1994; Fan et al. 1996; Harr et al. 2000; Rogers et al. 2003; Chen et al. 2004; Chen et al. 2006; Chen 2007; Dong et al. 2009) have been particularly attentive to research on heavy precipitation associated with TCs. Rodgers et al. (1994) summarized four environmental factors affecting TC precipitation over oceans. They are sea surface temperature, vertical wind shear, tropospheric moisture flux, and eddy relative angular momentum flux convergence in the upper troposphere. Chen (2007) pointed out that torrential rains by landfalling tropical cyclones were often associated with atmospheric environment, underlying surface, and generation and dissipation of internal mesoscale systems of TCs. TC extratropical transition (ET) and rejuvenation processes could also bring about unexpected heavy rainfall. A key factor (Dimego and Bosart 1982a,b; Harr et al. 2000; Bosart and Lackmann 1995; Foley and Hanstrum 1994; Li 2004) of the ET process is the interaction between a TC and a midlatitude westerly trough. Analyses by Bosart and Dean (1991) suggested that the interaction between cyclonic vorticity advection of an upper-level westerly trough and the remnant of Hurricane Agnes in the lower levels resulted in intensification of the TC after its ET, which led to frontogenesis and enhanced precipitation.

Atallah et al. (2007) investigated the relationship between TC tracks and the distribution of TC heavy rainfall in the eastern United States. Their results indicated that the rainfall distribution on the left side of the track was a result of an interaction between a TC and a westerly trough and thus the system was undergoing ET, whereas the rainfall distribution on the right side of the track was characterized by a TC interacting with a downstream ridge. Some analyses (e.g., Cheng 2008) show that a landfalling TC could be conducive for heavy rainfall when a low-level jet, strong upper-level divergence, and an unstable environment with low-layer high temperature and humidity exist. Previous research has focused mainly on the heavy rainfall that occurs when TCs make landfall. Fewer studies focus on rainfall reinforcement inland after TCs make landfall, especially those occurring in China.

Therefore, in this study the daily TC precipitation data for the period of 57 yr from 1949 to 2006 (excluding 2002) were used to establish the RRLTC criterion. Furthermore, studies of RRLTC statistical characteristics, a comparative study of scenarios of RRLTC and non-RRLTC using the composite data analysis, and explorations of RRLTC mechanisms and sources of energy will be carried out.

2. Data and methodology
The data used in this study include those of the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis data (2.5° × 2.5° horizontal grid spacing 4 times per day), those from the “Typhoon Yearbook” for TC tracks (published by the China Meteorological Administration; 1949–2006), daily TC precipitation data for the years from 1949 to 2006, and Chinese nationwide 6-hourly precipitation data for the period of 1998–2006 (those in 2002 were removed from the data analyses because of evident errors detected, and those for Taiwan were not included because of data incompleteness). The data used in the statistical calculations were the TC accumulated rainfall (defined as the sum of rainfall during a certain time period) over 24, 12, and 6 h, respectively. The 24-h TC precipitation data were provided by the Shanghai Typhoon Institute, China Meteorological Administration. These data are derived from a combination of rainfall observations from weather station rain gauges, as well as from remotely sensed data such as satellite images and radar data. It is the total observed rainfall of the weather stations, including TC remote rainfall (isolated rainfall resulting from TCs away from the TC center). The 6-h TC precipitation data were selected from Chinese national precipitation datasets for the same stations and the same days as those of the 24-h data. The 12-h TC precipitation data were aggregated from the 6-h data.

The variation of TC precipitation is expressed by tracking the time evolution of the averaged precipitation intensity. If the increments of the averaged precipitation intensity reached a certain criterion, those TCs were defined as RRLTC. Since the offshore precipitation data during TC landfall are not available, the TC precipitation for the day of landfall is not accounted for in the statistics.
This ensures that the precipitation records over the observing stations correctly reflect the characteristics of the entire TC precipitation. The detailed methodology for computing RRLTC is given below.

Within a given time interval $\Delta t$ (5 h, 24, 12, and 6 h, respectively), a set of accumulated rainfall amounts (mm) are obtained at different spatial locations $R_t$ (where the subscript $t$ denotes time). Among this set of rainfall observations, we first find the maximum rainfall amounts $R_{t1}$, the location of which is determined as the rainfall center. Within a radius of $R_{0(2, 3)}$ of latitude/longitude of this rainfall center, two other submaxima are located, $R_{ti}$ $(i = 2, 3)$. The averaged rainfall amount at time $t$ (where $t$ is a time sequence number for the rainfall observations after TC made landfall; i.e., the first, second, third observations, and so on) is then calculated by

$$R_t = \frac{1}{3} \sum_{i=1}^{3} R_{ti} \quad (t = 1, 2, 3, \ldots). \quad (1)$$

Next, a set of rainfall reinforcement intensities, recorded as $\Delta R_t$ (the rainfall difference for a particular time interval), can be calculated by taking the difference of the averaged rainfall amounts between two time levels:

$$\Delta R_t = R_t - R_{t-1} \quad (t = 2, 3, \ldots). \quad (2)$$

Finally, the RRLTC is realized whenever the rainfall increment between two time levels equals or exceeds a threshold rainfall amount, defined as

$$\Delta R_c = [\Delta R_t] + 0.8\sigma,$$

where $[\Delta R_t]$ and $\sigma$ are the mean and standard deviation of $\Delta R_t$, respectively, obtained statistically from a large sample of historical data (341 landfalling TCs during the 57 yr from 1949 to 2006). The value 0.8 is derived empirically by considering that the threshold values should not be too low to dilute the signal reflecting the essential nature of RRLTC and not too high to prevent the collection of enough samples. With 57-yr TC precipitation data, we were able to determine the threshold values for RRLTC as 15, 12, and 10 mm for 24-, 12-, and 6-h rainfall accumulation, respectively (see Table 1).

## 3. Climatological characteristics of TC rainfall reinforcement

### a. Rainfall reinforcement for various accumulation times

From 1949 to 2006, there were 341 landfalling TCs recorded during the 57 yr. Those that made landfall in Hainan and Taiwan without further landfall in mainland China were excluded. Among them, 33 tropical cyclones possessed 24-h rainfall reinforcement, accounting for 9.7% of the total landfalling TCs, an average of 0.58 such cases each year. For each landfalling TC, rainfall reinforcement can occur more than once. Therefore, the number of occurrences of RRLTC generally exceeds the number of landfalling TCs with rainfall reinforcement. In total, the number of occurrences of RRLTC was 37, or 0.65 times per year on average.

In the period from 1998 to 2006, 6-h and 12-h precipitation data began to become available. During these eight years, the numbers of landfalling TCs with 12-h and 6-h rainfall reinforcements were 8 and 15, respectively (with the number of RRLTC occurrences were 10 and 30, respectively). This yields 1 and 1.9 RRLTC per year on average, about 17% and 31% of the total landfalling TCs in those eight years, for 12-h and 6-h time intervals, respectively. This indicates an increase in the number of landfalling TCs with rainfall reinforcement in the reduced time intervals. Table 2 provides all landfalling TCs with rainfall reinforcement, followed by the corresponding year and serial number of the TCs (in parentheses). It is worth noting that during 1998–2006, all landfalling TCs with 24-h rainfall reinforcement were included in those with 12-h rainfall reinforcement, and all landfalling TCs with 12-h rainfall reinforcement were included in those with 6-h rainfall reinforcement. This implies that RRLTC processes essentially take place in a short period of time (usually several hours).

### Table 1. RRLTC criteria for different durations.

<table>
<thead>
<tr>
<th>Duration (h)</th>
<th>24</th>
<th>12</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[\Delta R_t]$ (mm)</td>
<td>-43.6</td>
<td>-13.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>$\sigma$ (mm)</td>
<td>72.2</td>
<td>33.0</td>
<td>19.9</td>
</tr>
<tr>
<td>$\Delta R_c$ (mm)</td>
<td>15</td>
<td>12</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 2. RRLTC cases. The length of the data for 24, 12, and 6 h were 57, 8, and 8 yr, respectively.

<table>
<thead>
<tr>
<th>Duration (h)</th>
<th>China Meteorological Administration code</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>4906, 5218, 5310, 5407, 5622, 6007, 6120, 6205, 6306, 6312, 6611, 6706, 6909, 7010, 7416, 7503, 7504, 7805, 8107, 8108, 8506, 8609, 8913, 9012, 9018, 9417, 9608, 9711, 0010, TD(2001/9), 0513, 0604, 0605</td>
</tr>
<tr>
<td>12</td>
<td>9909, 0010, TD(2001/9), 0421, 0509, 0513, 0604, 0605</td>
</tr>
<tr>
<td>6</td>
<td>9908, 9909, 0008, 0010, 0013, 0104, TD(2001/9), 0414, 0421, 0509, 0510, 0513, 0604, 0605, 0606</td>
</tr>
</tbody>
</table>
decreased time interval, the timing of RRLTC can be defined more accurately. Because of the limited availability of 12-h and 6-h data, the analyses below will mainly focus on 24-h RRLTC characteristics.

b. The interannual, monthly, and diurnal variability

Figure 1 describes interannual variability of rainfall reinforcement of landfalling TCs. The number of RRLTC occurrences (times) varies between 0 and 4. The years 1981 and 1975 are quite distinctively significant, with three and four occurrences per year. No trend can be identified for the variation in frequency. The interannual variability in rainfall reinforcement intensity was quite prominent with the strongest occurring in 2005, reaching 184.7 mm (24 h)$^{-1}$, which is 3.1 times the average. The rainfall reinforcement intensity presented a linear trend but was trivial except for the most recent 10 yr, during which the rainfall reinforcement intensity increased markedly and passed a 0.05 significance test.

Occurrences of rainfall reinforcement of tropical cyclones were concentrated in July, August, and September (see Fig. 2). The maximum number of reinforcement cases occurred in August, accounting for 48.7% of the total (18 of 37 events), followed by July and then September. The monthly change of RRLTC frequency agrees with that of landfalling TCs (i.e., more landfalling TCs provide more possibilities for the occurrence of rainfall reinforcement). There was not much variation in rainfall reinforcement intensity. However, the rainfall intensities for July, August, and September did not pass a statistical test at the significance level of 0.3.

The rainfall reinforcement occurrences had a slight diurnal variation (not shown) with the highest frequency at 0200 local standard time (LST; 1800 UTC) and the least at 2000 LST (1200 UTC). The rainfall reinforcement intensity was the strongest at 0200 LST (1800 UTC) in the early morning, with 6-h reinforcement reaching 27.3 mm, while the weakest was at 2000 LST (1200 UTC) with the reinforcement of 14.3 mm (6 h)$^{-1}$. The strongest rainfall reinforcement in the early morning may be correlated with the cooling of the cloud top, resulting in unstable stratification. One possible explanation of this phenomenon proposed by Kraus (1963) is as follows. During the day, cloud cover prevents solar radiation from warming up the surface and the cloud base. Meanwhile the cloud top warms more than the cloud base. As a result, the lapse rate inside the cloud is relatively small. From nighttime to

![Fig. 1. Interannual variability of RRLTC occurrence frequency and intensity from 1949 to 2006.](image1)

![Fig. 2. Averaged monthly variability of RRLTC occurrence frequency and intensity from 1949 to 2006. The standard deviations of intensity for July, August, and September are 44.4, 33.5, and 59.1 mm (24 h)$^{-1}$, respectively.](image2)
early morning, when there is no solar radiation, cloud tops cool more than cloud bases, which receive ground emissions and are thus warmer. This results in larger instability for nighttime and early morning than during the day. Another possible explanation for the morning rainfall maximum may be related to the mechanism proposed by Gray and Jacobson (1977). They showed that vertical motion could result from solenoidal circulations forced by the difference in nocturnal radiative cooling between cloudy and clear areas. The instability of the air below and within the cloud should be favorable for rainfall.

c. Rainfall reinforcement in relation to topography

Many previous studies have revealed that topography plays an important role in causing heavy precipitation of landfalling TCs (Chen and Ding 1979; Tao et al. 1980; Bosart and Dean 1991; Wu 2001; Wu et al. 2002; Chen 2006; Smith et al. 2009a,b; Gao et al. 2009). Topography convergence strengthening upward motion in the mountain slope against wind constitutes a basic contribution to rainfall increase and often leads to asymmetric rainfall distribution of landfalling TC, with significant rainfall on the wind side and much less rainfall in the lee side.

In Fig. 3, we plotted the positions of 33 rainfall reinforcement centers for 24-h accumulation (solid triangles) in relation to the topography in China (shaded). One can see that these RRLTC centers were mainly located near coastal lines and on the eastern and southern slopes of mountain ridges, accounting for 49%, 22%, and 16% of the total occurrences, respectively. The maximum rainfall reinforcement of 184.7 mm (24 h)\(^{-1}\) recorded so far was brought about by Typhoon Talim (0513) in the area of Dabie Mountain and was primarily associated with ascending air motion by the topographic forcing (He et al. 2006). The second strongest RRLTC center occurred in the Liaodong Peninsula as a result of a tropical storm (TS; 8108) moving northward. The center may have been caused by ET as well as local topography.

From these analyses, it is evident that terrain has a significant impact on rainfall reinforcement of landfalling tropical cyclones by increasing the intensity through lifting enhancement. We are currently conducting a numerical simulation study in an attempt to assess the extent of topographic impact on RRLTC. Results will be reported in a forthcoming paper.

d. Rainfall reinforcement in relation to TC tracks

The majority of the TCs originated over the ocean area east of the Philippines and moved northwestward to make landfall in the coastal provinces Zhejiang and Fujian (see Fig. 4). Statistics on areas where TCs made landfall with rainfall reinforcement reveal that 83.8% of the TCs (31 of 37 events) made landfall in coastal Zhejiang and Fujian province, and 56.8% among them were in Fujian province alone. The TCs followed tracks mainly in two directions with high frequency (Fig. 4). The first is the northward track (denoted by the thick solid lines with an arrow in the diagram shown, denoted T1). Typhoon Fred, which induced heavy torrential rain in 1994 in eastern China, is an example of a storm in this track category. The second track takes a predominantly westward direction (indicated in the figure by the thick solid line with an arrow, denoted T2). One example was the severe Tropical Storm Bilis (0604) that caused serious casualties and flooding in 2006. The total TCs with rainfall reinforcement took 51.5% and 27.3% of the two above tracks respectively.

e. Rainfall reinforcement in relation to intensity of TCs at landfall

Figure 5 shows that the occurrence frequency of RRLTC was approximately proportional to the TC intensity (TC category) at landfall. For example, the largest proportion of RRLTC (48.6%; 17 of 37 events) is induced by landfalling typhoons. Statistical results (Li 2004) suggested that the stronger the intensity of the landfalling TCs, the longer they would sustain over land, increasing the likelihood that RRLTC would occur. We should emphasize that although the occurrence frequency of RRLTC induced by TDs was the lowest, the RRLTC intensity associated with TDs could be the strongest, with the average reinforcement reaching 98.6 mm (24 h)\(^{-1}\).

These results illustrate that RRLTC intensity is not simply proportional to the TC intensity at landfall. The landfalling TC remnant is also capable of generating
exceptionally strong rainfall reinforcement. For instance, the rainfall reinforcement by TD 0109 in 2001 was as much as 111.7 mm (24 h)$^{-1}$ and resulted in an extraordinarily heavy downpour of 278 mm (24 h)$^{-1}$ in Shanghai on 6 August. Some studies (Yang et al. 2004; Qi and Zhao 2004) demonstrated that plentiful moisture and symmetric instability provided conditions associated with RRLTC that were favorable for the formation of meso-$\beta$ convective clouds.

f. Rainfall reinforcement in relation to TC intensity at the time of RRLTC

The relationship between rainfall reinforcement and TC intensity at the time when the RRLTC was generated is shown in Fig. 6. About 85.3% of RRLTC cases occurred at TD intensity, whereas only a small percentage of RRLTC occurrences happened at TS and severe tropical storm (STS) intensities; at 8.8% and 5.9%, respectively. Furthermore, the rainfall reinforcement intensity was the strongest [67.7 mm (24 h)$^{-1}$] when the TC was in the stage of a TD, and the weakest [26.5 mm (24 h)$^{-1}$] in the stage of an STS. The low intensity in STS is statistically significant at the significance level of 0.3. These results reveal that even when a landfalling TC was downgraded to a TD, the remnant could still be capable of bringing about extraordinarily heavy downpour.

g. Timing characteristics of TCs with rainfall reinforcement

An analysis of the relationship between the landfalling time and the time of occurrence of rainfall reinforcement is shown in Fig. 7. It can be seen that RRLTCs typically occur between three and five days after a TC landfall; 24 out of 37 RRLTCs (64.9%) occurred on the third day.
after a TC landfall, with the occurrence frequency of rainfall reinforcement decreasing with time. This trend is likely related to the lifespan of TCs over land, most of which is about three days. Fewer TCs can sustain for five days. However, the strongest rainfall reinforcement intensity occurred during the fifth day after a TC landfall. We should pay more attention to this in operation.

Interestingly, the highest intensity coincides with the lowest frequency of RRLTC in both Figs. 5 and 7.

**h. Rainfall reinforcement in relation to TC translational speed**

Some studies (Chen and Ding 1979; Tao et al. 1980) demonstrated that TC-induced heavy rainfall often occurred when the TC was in the stage of being sustained or stagnated. For instance, Typhoon Gloria slowed down while moving into the Bai-xin county of Taiwan province on 10–12 September 1963 and caused a 1248-mm downpour within a 24-h period. Chen et al. (2006) showed that the translational speed had an important impact on TC rainfall in the low-shear environment. Figure 8 shows a comparative analysis between the translational speed at the time of rainfall reinforcement and a mean translational speed from one day before to one day after the reinforcement. It suggests that about two-thirds of RRLTC move below 5 m s\(^{-1}\) and 61% of those occurred in the period when the TC slowed down. For instance, Typhoon Talim (0513) moved at 1.2 m s\(^{-1}\) during rainfall reinforcement whereas it had an average moving speed of 3.5 m s\(^{-1}\); similarly, Typhoon Jeff (8506) moved at a speed of only half of its average during its rainfall reinforcement. This analysis shows that RRLTC typically occurs when a TC slows down. Low translational speed or stagnation of TC could cause the rainfall to concentrate on a certain area and result in an enhanced accumulation of rainfall locally.

![Days after landfalling time](image)

**Fig. 7.** Relationship between RRLTC occurrence frequency and intensity with days after TC landfall. The standard deviations of intensity for 3 and 4 days after landfall are 40.7 and 38.6 mm (24 h)\(^{-1}\), respectively. (Note: there are too few cases to calculate the standard deviation in the fifth day after landfall).

![Translational speed at reinforcement](image)

**Fig. 8.** The translational speed at RRLTC and the mean translation speed from 1 day before the reinforcement to 1 day after that and the ratio of the former to the latter. From left to right, the rule of sorting these 33 cases is according to the decrease of ratio of translational speed at reinforcement to the mean.
In the U.S. operational forecast guideline for TC rainfall, there is a well-known “Kraft’s rule of thumb,” which consists of dividing a constant value by the translational speed of the storm. For slow-moving systems whose translational speed approaches zero, the peak rainfall would be very high (Pfost 2000; Rogers et al. 2009). Moreover, there is a clear distinction between RRLTC and non-RRLTC cases. The mean translational speeds are 5.6 m s$^{-1}$ for RRLTC and 6.9 m s$^{-1}$ for non-RRLTC cases. The ratio of the former to latter is 81%. This indicates that TCs with a low translational speed tend to induce RRLTC.

i. Location of RRLTC relative to TC centers

A TC is a moving system, whereas 24-h rainfall is an accumulated variable in one day. Therefore, an analysis was carried out for the center of RRLTC relative to the average position of TC centers during those 24 h. From Fig. 9a, it can be seen that the frequency of RRLTC centers was inversely proportional to the distance from the TC centers. About 52.9% of RRLTC centers fell within 2.5° of distance from the TC centers. The intensity of rainfall reinforcement increased first from the TC center and then decreased with respect to distance. The maximum intensity of 85.3 mm (24 h)$^{-1}$ between 2.5° and 5° and the minimum intensity of 27.3 mm (24 h)$^{-1}$ between 7.5° and 10° of distance from the TC center are both statistically significant at the significance level of 0.3.

Statistics showed that 35.3% of rainfall reinforcement occurred in both northeast and southwest quadrants, respectively, with the fewest cases occurring in the northwest (Fig. 9b). The strongest rainfall reinforcement usually occurred in the northeast quadrant, reaching 80.5 mm (24 h)$^{-1}$, which is statistically significant at the significance level 0.3. The weakest rainfall reinforcement [33.2 mm (24 h)$^{-1}$], which typically occurred in the northwest quadrant, also passed the statistical test at the 0.3 significance level.

Furthermore, statistics of the RRLTC centers for TCs with northward (southward) tracks show that the northeast (southwest) quadrant was the highest frequency region, accounting for 40.9% (45.5%) of rainfall reinforcement. Based on these results, we chose RRLTC samples of both the northward-moving category with rainfall centers in the northeast quadrant and the westward type with rainfall centers in the southwest quadrant to synthesize and analyze in the next section.

4. Atmospheric circulation characteristics associated with RRLTC

The above analyses illustrated that RRLTC occurred mainly in the two lines of TC tracks (i.e., in the northward and westward tracks). Next we would like to examine characteristics of atmospheric circulation associated with these two RRLTC tracks.

A dynamic composite technique (Li 2004) was used for such an analysis. In this method, the composite region moves with the TC. The center of the composite region is the center of the TC. At any given time $t$, the value of a composite variable $\bar{S}$ at a particular point $(x, y)$ is calculated by

$$\bar{S}(x, y, t) = \frac{1}{N} \sum_{n=1}^{N} S_n(x, y, t),$$

where $(x, y)$ is the grid number from west to east (south to north) in the composite region, $S_n(x, y, t)$ denotes the value of the variable for a certain TC case at point $(x, y)$ at that time, and $N$ is the number of total TC cases considered. Therefore, $\bar{S}(x, y, t)$ is the average of a number of cases in the composite region. This procedure can be carried out for a set of times, from which we may obtain a time series of each composite variable. Figure 10 shows the schematic of the TC tracks (dashed lines with arrows) and dynamic composite regions (rectangles). Keeping the TC site in the center of the study region in this method will help to reduce excessive smoothing of the variables. By doing this, the TCs’ structure and the original location of ambient atmospheric systems relative to the TCs will remain unchanged.

By grouping similar TC tracks, rainfall reinforcement intensity, and quadrants for rainfall reinforcement (northward type in the northeast quadrant, westward type in the southwest quadrant), samples of the RRLTC category were selected. Four cases (6205, 6306, 8108, and 9417) were selected for the northward type and three cases (6120, 8107, and 0605) for the westward type.
Likewise, the non-RRLTC category was sampled following tracks similar to the above. Four cases (8209, 9418, 9504, and 9909) for the northward type and three cases (8404, 8817, and 9803) for the westward type were selected. The duration of synthesis was chosen for three days, denoted D1, D2, and D3. For the RRLTC category, the synthetic analysis was conducted for two days prior to the reinforcement and one day during the reinforcement, and for the non-RRLTC category, the synthetic analysis was done for the day of TC landfall and two additional days. Since 24-h rainfall is an accumulative variable (a consecutive record during the whole day) but observations are instantaneous variables (such as geopotential height, wind, moisture, and temperature, available 4 times per day), the atmospheric circulation was taken as an average of the 4-time observed values of the day, which would be more consistent with the rainfall analyses.

a. Large-scale circulation characteristics for TCs with a northward track

Evolution of atmospheric circulations at 200 hPa revealed that at this outflow layer, both the reinforcement TC and the non-RRLTC were under a subtropical anticyclone (Figs. 11a,b). This is characteristic of a tropical cyclone maintaining itself after landfall. The difference is that the divergence (shown by the dashed lines in the figure for contour lines $\approx 4 \times 10^{-6}$ s$^{-1}$) in the upper layers was stronger for the reinforcement TC than for the non-RRLTC, especially on the north side of the TC. On the day with rainfall reinforcement (see Fig. 11a),

Fig. 10. Schematic of TC tracks (dashed lines with arrows) and dynamic composite regions (rectangles). Here, \( + \cdots = \Sigma \) denotes \( \Sigma S \), which is the sum of each sample for variable \( S \). Then, \( \Sigma S \) is used to derive \( \bar{S} \) based on Eq. (4).

Fig. 11. Composite flow field (streamlines), jets (shaded; m s$^{-1}$), and divergence (dashed curves; 10$^{-6}$ s$^{-1}$) at 200-hPa level for (a) a reinforcement TC and (b) a non-RRLTC TC with a northward track. The TC centers are located in the origin of the coordinates in latitude and longitude. The coordinates are positive in eastward and northward directions and negative in westward and southward directions. The box connecting the TC center denotes the high-frequency regions for rainfall reinforcement.
there existed a divergence zone on the south side of the entrance of the southwesterly jets entering the northern side of the northeast quadrant of the TC. The existence of the divergence zone was typically located on the right side of entrance region of the jet streak—a favorable region for ageostrophic forcing of upward motion (Rossby 1938; Riehl et al. 1954; Sechrist and Whittaker 1979) and rainfall enhancement therein. This is also consistent with Ding et al. (2001) in that precipitation would be intensified if the TC were located in the rear right of a southwesterly jet in the upper atmospheric layers.

The geopotential height at 500 hPa (Figs. 12a–f) shows that both the reinforcement TC and the non-RRLTC TC are controlled by a meridional circulation. This is a common characteristic for TCs with a northward track. For the westerlies associated with the reinforcement TCs (Figs. 12a–c), there existed a westerly trough (thick solid lines) and a zonal frontal area, which the TC with a northward track was approaching. On the day of reinforcement when the TC was entering the baroclinic frontal zone, there occurred a north–south superimposition of the TC and the westerly trough, leading to a development of a very deep trough. Variations of vorticity illustrate clearly the merging of the zones with positive vorticity between the TC and the westerly trough (shaded area). In the case of the non-RRLTC (Figs. 12d–f), only a shallow westerly trough was found approaching the TC. No north–south superimposition of the TC and the westerly trough and no company of the evident frontal zone could be identified.

Results from the study by Li (2004) show that the TC would acquire baroclinic potential energy by the interaction with a westerly trough, leading to an enhancement of precipitation. The approaching of a frontal zone is indicative of an intrusion of cold air in the middle and upper layers, which enhances instability of the atmosphere.
Numerical experiments by Xu et al. (1998) demonstrate that a strong baroclinic structure of a front in the environment could result in TC intensification by extratropical transition and upward motion enhancement near the front and hence increase rainfall therein. Therefore, the superimposition of the TC and westerly trough was an important characteristic process for the RRLTC. The evolutions of low-level jets for the two categories of TCs (reinforcement TCs and non-RRLTCs) displayed significant differences (not shown). In the case of a reinforcement TC, a low-level jet typically appeared on the east side of the reinforcement TC for all three days. However, the low-level jet was very weak in the case of the non-RRLTC and almost disappeared at D3. This would lead to a difference in moisture transport in the lower levels (Fig. 13). From D2 to D3, great moisture fluxes and a long channel of moisture transport (Figs. 13b,c) existed for the reinforcement TC cases, which are conducive to the sustained moisture influx of the TC remnant. On the contrary, for the non-RRLTC cases, not only weak moisture fluxes but also the breakdown of the moisture channel (defined as the high moisture flux region where moist flux exceeds 8 g hPa$^{-1}$ cm$^{-1}$ s$^{-1}$) were apparent (Figs. 13e,f).

From the above analyses, we can thus conclude that the major differences between the reinforcement TC and the non-RRLTC with a northward track lie in two significant characteristics: 1) interaction between a TC remnant and midlatitude westerly trough and its frontal zone and 2) the availability of strong low-level moisture transport.

b. Large-scale circulation characteristics for TCs with a westward track

At the 200-hPa pressure level (Figs. 14a,b), anticyclonic divergence associated with the South Asian high belt dominates over TCs with a westward track. However, it should be noted that the divergence to the south of the TC is stronger for the reinforcement TC than for the non-RRLTC.
The circulation patterns at the 500-hPa level (Figs. 15a,b) display that the two categories of TCs (reinforcement TC and non-RRLTC) shifted westward under the steering easterly current in the southern periphery of the subtropical high. The frontal zone in the midlatitude was quite a distance from the TC to the north, leaving no possibility for the TC to be superimposed with a midlatitude westerly trough.

The major differences between the reinforcement TC and the non-RRLTC were concentrated on the low-level circulation characteristics (Figs. 16a–f). The existence of reinforcement TCs was supported by a strong

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**FIG. 14.** As in Fig. 11, but for the westward track.

**FIG. 15.** As in Fig. 12, but for the westward track. (The “C” at left denotes a cyclonic vortex.)
southwesterly jet, which was directly connected to the landfalling TC. The enhancement of the southwesterly jet may connect with the deepening of a trough that corresponded with a developing cyclonic vortex ("C" in the figure) at 500 mb (Fig. 15a) to the west of the TC. Accordingly, the reinforcement TC had higher moisture fluxes (Figs. 16a–c). In contrast, the non-RRLTC not only exhibited weak moisture fluxes but also lacked a continuous moisture transport channel. One case in point, as we mentioned earlier, was the severe Tropical Storm Bilis (0604) that produced torrential rainfall when moving westward after landfall.

According to composites, monsoon surge [defined as the regional mean 850-hPa southwesterly enhancement over the northern South China Sea (10°–20°N, 105°–120°E) during a short period] was one of the major causes for the enhancement of precipitation for westward moving cases. There are still some other mechanisms such as topography, vertical wind shear, warm-air advection, and frontogenesis (Gao et al. 2009) that contribute to heavy rainfall. Two typical examples of monsoon surges during July 2006 are displayed in Fig. 17, where the wind speed is an area mean of total wind over the northern South China Sea (10°–20°N, 105°–120°E) at 850 hPa; they clearly illustrate that there were two monsoon surges affecting China. Surge 1 (S1) and S2 relevant to Bilis (0604) and Kamei (0605), respectively.

c. A comparison of energy sources for the two categories of TCs

The remnant of a landfalling TC would typically dissipate rapidly because of the cutoff of energy supply from ocean-surface evaporation and the effects of land surface friction. Therefore, the observed rainfall reinforcement from a remnant of a landfalling TC implies that the remnant must have been acquiring energy from new sources. The statistical results earlier revealed that landfalling TC remnants with rainfall reinforcement were mainly found in motion along two tracks, the northward and westward tracks. Diagnostic analyses of circulation characteristics indicated that the reinforcement TC with a northward track was correlated with a superposition of
a westerly trough in the midlatitude and an intrusion of cold air at the middle and upper layers. These circulation characteristics provide favorable conditions for the landfalling TC remnants to gain access to the baroclinic potential energy, defined as that part of potential energy [PE; Eq. (5), where $g$ and $z$ respectively represent gravitational acceleration and geopotential height] that could be released and converted into kinetic energy. On the other hand, the reinforcement TC with a westward track is associated with a large magnitude moisture flux [MMF; Eq. (6), where $q$ is the specific humidity and $V$ is a wind vector] by southwesterly flows, which help the landfalling TC remnant acquire a large amount of latent heat [LH; Eq. (7), where $L$ denotes condensation coefficient].

In the following, calculations of different forms of energy and related variables were carried out for the RRLTC with two different tracks, using the following formulas:

$$PE = gz,$$  \hspace{1cm} (5)

$$MMF = \frac{1}{g} qV$$ \quad \text{and} \quad (6)

$$LH = Lq.$$ \hspace{1cm} (7)

The detailed calculation procedure is as follows: let variable $A$ be an area-mean value of a physical variable in the area of rainfall reinforcement at a given time. The mean area for the northward (westward) track is one with $10^\circ \times 10^\circ$ on the sides of a northeast (southwest) quadrant of a TC. Let $\langle A \rangle$ represent the 48-h average of $A$ for the day prior to and on the day of rainfall reinforcement, and $A'$ as the perturbation of $A$, which is calculated every 6 h. With all these definitions, $A$ can be expressed as

$$A = \langle A \rangle + A'.$$ \hspace{1cm} (8)

Therefore, Eqs. (5)–(7) can be decomposed as Eqs. (9)–(11):

$$PE = \langle PE \rangle + PE',$$ \hspace{1cm} (9)

$$MMF = \langle MMF \rangle + MMF',$$ \hspace{1cm} (10)

$$LH = \langle LH \rangle + LH',$$ \hspace{1cm} (11)

$$T = \langle T \rangle + T'.$$ \hspace{1cm} (12)

Equations (9)–(12) were used to compute the perturbations, namely $PE'$, $MMF'$, $LH'$, and $T'$ for potential energy, magnitude moisture flux, latent heat, and temperature, respectively, over the area with rainfall reinforcement. Then quantitative comparisons of these perturbed fields are conducted. Because of the small numbers of cases (three or four), analyses for statistical significance are not possible.

To observe the variation of composites at the time of onset and duration of rainfall reinforcement, the time
Figure 18. Evolution of the perturbations of (a) $T$ (K), (b) $PE$ (J kg$^{-1}$), (c) MMF$^t$ (g hPa$^{-1}$ cm s$^{-1}$), and (d) LH$^4$ (J kg$^{-1}$) for the northward TC track (dashed lines) and the westward TC track (solid lines), at (a), (b) 500 hPa and (c), (d) 850 hPa. The abscissa represents time (h) relative to the onset of rainfall reinforcement; negative (positive) values denote the time before (after) the onset.

Figure 19. As in Fig. 18, but for RRLTC cases (solid lines) and non-RRLTC cases (dotted lines).

The coordinate were changed, letting time 0 denote the onset time of rainfall reinforcement. In Fig. 18, negative (positive) values in abscissas denoted the time before (after) the beginning of the RRLTC in hours. Computational results showed that for the reinforcement TCs in the northward and westward tracks, significant differences could be identified in the evolution of the perturbation of the temperature in the middle and upper layers. For the northward TC track (Fig. 18a), there appeared to be a significant negative anomaly in the reinforcement period (0–24 h). Six hours after the onset, an intrusion of cold air was signified by a 1.2°C drop in temperature at 500 hPa, compared with that before the onset. Also, there was a cold air intrusion from the bottom, which was favorable for lifting the warm air and hence increasing the rainfall. The evolution of the potential energy perturbation (Fig. 18b) also demonstrated that the intrusion of cold air enabled the release of potential energy.

Studies (Chen and Ding 1979) have shown that during cold air intrusion, the front enhances and thus enlarges vertical motion, with cold air sinking and warm air ascending. This results in potential energy being converted into kinetic energy, thereby strengthening horizontal winds in the lower troposphere and causing the TC central pressure to drop (with a mutual adjustment between the wind and pressure fields). Consequently, the TC would redevelop and hence help to increase rainfall. Comparatively speaking, variations of perturbations of temperature and potential energy (Figs. 18a,b) were much weaker for the reinforcement TCs with a westward track (solid curves). It is thus evident that the intrusion of cold air in the middle and upper layers of the atmosphere could be an important signal indicative of rainfall reinforcement for RRLTCs with a northward track, and that the release of potential energy should be an important mechanism inducing rainfall reinforcement.

There were also differences in humidity perturbation in the lower layer for the reinforcement TCs in the two categories of tracks. For the reinforcement TCs with a westward track (Fig. 18c), the anomaly of moisture flux perturbation in the lower layer was positive during the day of reinforcement (0–24 h). This signifies that moisture fluxes at 850 hPa were dramatically increased at 6 h, with the simultaneous release of latent heat as large as 1200 J kg$^{-1}$ into the atmosphere (Fig. 18d), which indicates the occurrence of heavy condensation leading to an increase in rainfall. In contrast, for the reinforcement TCs with a northward track, as displayed by the dashed curves in Fig. 18c, the moisture flux perturbation exhibited fluctuation. This indicates that a certain level of moisture input existed, but with no clear signal in the period (0–24 h) of the reinforcement. Correspondingly, the release of latent heat (Fig. 18d) was much weaker than that of the westward track and occurred in the late period (18–24 h) of the reinforcement. This indicates that the strengthened moisture transport could be an important precursor for rainfall reinforcement for the reinforcement TCs with a westward track, and that release of a large quantity of latent heat could be an important source of energy triggering rainfall reinforcement.

Further comparison of energy sources between RRLTC and non-RRLTC cases in Fig. 19 also shows that there are obvious cold air intrusions and potential energy releases in TCs with northward-moving cases undergoing RRLTC,
but no such characteristic exists in non-RRLTC cases (Figs. 19a,b). For westward moving TCs (see Figs. 19c,d), RRLTC cases exhibit an enhanced moisture transport and latent heating as well as the potential for latent heat release, but no such signals are seen in the non-RRLTC cases.

The results from the above analyses reveal that rainfall reinforcement of landfalling TCs requires the acquisition of new energy. There are two possibilities for new sources of energy. One is from baroclinic potential energy brought about by an intrusion of cold air in the middle and upper layers of the atmosphere. This process mostly occurs for the reinforcement TCs with a northward track. The other energy source is the release of latent heat supplied by an enhanced moisture transport due to monsoonal surges. The second process often occurred for the reinforcement TCs with a westward track.

5. Summary and discussion

In this study, we first established RRLTC criteria with explorations of their climatological characteristics and the large-scale factors that may influence their existence. The following conclusions can be drawn from these analyses:

1) RRLTC possesses a relatively low probability of occurrence (about 9.7% of total landfalling TCs are recorded with rainfall reinforcement). The frequency and intensity of the RRLTC exhibit significant annual variability and present an increasing trend in intensity for the last 10 yr. The occurrences of RRLTC were concentrated in the period from July to September with the maximum in August. The reinforcement mostly occurred during the second day and its intensity peaked on the fourth day after a TC landfall.

2) Storms with slow translational speed are conducive to RRLTC. Coastline vicinities and the southern and eastern slopes of mountains in China are favorable regions for rainfall reinforcement. The occurrence frequency of RRLTC is proportional to the intensity of landfalling TCs, but the most intense RRLTC often originate from landfalling TDs. When TCs are weakened to the TD stage with slow motion or stagnation, they likely develop into very intense RRLTC. The centers of rainfall reinforcement are then likely situated in the northeast and southwest quadrants of a TC for northward and westward moving TCs, respectively.

3) TCs with potential rainfall reinforcement predominantly made landfall along the coasts of Zhejiang and Fujian provinces in China. Once making landfall, they typically traveled either northward or westward. Diagnostic analyses on large-scale circulations showed that TCs with a northward track characteristically tended to merge with midlatitude westerly troughs and low-level jets, where channels for moisture supply are maintained. TCs with a westward track were primarily characterized by their linkage to low-level southerly flows or monsoon surges and corresponding water vapor channels, which resulted in a large quantity of water vapor supply. These characteristics are clearly absent in non-RRLTCs.

4) The remnants of landfalling TCs can be sustained without decay and can reinforce precipitation as they acquire energy from new sources. From the analyses, we found that the new energy came from (a) baroclinic potential energy due to an intrusion of cold air, which usually occurred for TCs with a northward track, and (b) an increase of moisture transport due to monsoonal surges for those TCs with a westward track.

Our finding of the trough–TC interaction being favorable to rainfall reinforcement agreed with the conclusion given by Bosart and Carr (1978) that a shortwave trough in the mid- and upper troposphere was an important factor contributing to the heavy rainfall associated with Agnes (1972). Moreover, their schematic model also showed that the heaviest rainfall occurred in the northeast quadrant of the TC, which was consistent with the location of the highest frequency in statistics for TCs with northward tracks. However, there was no obvious asymmetric structure of temperature as half-warm and half-cold to prove TCs had undergone an extratropical transition. That is to say, the TC–trough interaction, even without the resulting ET, could also induce RRLTC. Some case studies (Dimego and Bosart 1982a,b; Harr et al. 2000) have illustrated that TCs could redevelop through the ET process and enhanced upward motion to favor an increase in rainfall. Considering that our results were based on a composite analysis, the ET process was merely one of the mechanisms that prompted RRLTC. Our composite results also indicate that rainfall enhancement for westward moving TCs are related to monsoon surge, which agrees with the case study conducted by Gao et al. (2009).

Combining the above statistics and composite results, we can conclude that large-scale circulation and topography play important roles in the location of reinforced rainfall centers. For northward moving TCs, the rainfall centers tend to situate in the northeast quadrant of the TC. There are two reasons for this: one is that there are favorable large-scale conditions, such as strong upper-level divergence, maintenance of low-level jet, and
moisture transfer. The other is that warm and moist southeasterly flow in the northeast quadrant of TC is lifted by topography and results in rainfall increase along the southern or eastern slope of mountains in eastern China. For westward moving cases, rainfall centers tend to situate in the southwest quadrant of the TC. The reasons are as follows. First, there are favorable large-scale conditions such as strong upper-level divergence and the existence of a monsoon surge to provide abundant moisture at low levels. Second, warm and moist southeasterly flow in the southwest quadrant of the TC is raised by topography and leads to enhanced rainfall along the southern slope of mountains in southern China.

According to these analyses, there are different forecasting considerations for RRLTCs with northward tracks and westward tracks. For the northward type, forecasters should carefully examine whether the TC will interact with the westerly trough and consider the maintenance of the moisture supply and the underlining terrain. For the westward type, they should pay more attention to the TC’s possible reinforcement by a monsoon surge as well as the topographic impact.

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