Surface Fluctuations Associated with Tropical Cyclone Rainbands Observed near Taiwan during 2000–08

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ABSTRACT

With radar measurements and temporally high-resolution surface observations, this study investigates surface fluctuations associated with tropical cyclone rainbands (TCRs) observed in the vicinity of Taiwan during 2000–08. A total of 263 TCRs identified from 37 typhoon events during the study period were analyzed to show the mean and common nature of perturbations of various meteorological variables associated with the passage of TCRs.

The main patterns of surface thermodynamic fluctuations, as revealed from the composite analysis of all identified TCRs, include a persistent decrease in temperature, dewpoint temperature, and equivalent potential temperature $\theta_e$ from the outer to inner edge of the rainband. A wavelike variation of pressure perturbations associated with the rainband was evident, with a minimum coincident with the outer edge and a maximum located inside the inner edge. The kinematics of the rainband was characterized by an obvious decrease in cross-band wind component, relatively minor variations in along-band wind component, and the wind veering. Quantitative analyses indicate that the majority of the TCRs ($\sim$80%–90%) exhibited variations in surface temperature, pressure, wind speed, and wind direction less than 2°C, 1.5 mb, 5 m s$^{-1}$, and 20°, respectively. However, a clear trend of the magnitude of TCR thermodynamic fluctuations increasing with the radial distance from the tropical cyclone center was observed.

The TCRs identified in this study were also classified into the outer and inner rainbands, which are distinguished by a radial distance of 3 times the radius of maximum wind. The composite and magnitude analyses of their surface fluctuations indicate that the outer rainbands had a higher potential than the inner rainbands to reduce the near-surface $\theta_e$ values. This observed characteristic is likely related to more pronounced evaporative cooling taking place in drier subcloud regions and the downward transport of low-$\theta_e$ air aloft by more vigorous convective downdrafts for the outer rainband. Fundamentally different features of surface pressure fluctuations and mean frictional vertical velocity and relative vorticity between the outer and inner rainbands were also documented. These results reflect a possibly different origin. Nevertheless, there was no dramatic difference in the pattern of kinematic fluctuations between the outer and inner rainbands, and their mean magnitudes were also found to be statistically identical, which suggests that there is not an entirely clear distinction of surface characteristics for these two types of rainbands.

1. Introduction

The tropical cyclone rainbands (TCRs) are one of the most striking and persistent features of tropical cyclones (Wexler 1947; Senn and Hiser 1959; Willoughby et al. 1984; Gall et al. 1998; Cecil et al. 2002; Houze 2010). Outside the eyewall region, TCRs are a primary, concentrated region of heaviest precipitation within tropical cyclones (Anthes 1982; Jorgensen 1984). The origin of TCRs and their possible roles in influencing the intensity of tropical cyclones have received considerable attention in the past few decades; however, dynamic processes implicit in these scientific issues are still in great debate and remain unresolved (e.g., Willoughby et al. 1982; Shapiro and Willoughby 1982; Barnes et al. 1983; Willoughby 1990; May and Holland 1999; Houze et al. 2006; Wang 2009).

Perhaps the most crucial approach to advancing our understanding of the aforementioned aspects is to fill the gaps in our knowledge of the TCR structural characteristics close to the surface, because the heat and moisture sources of convective energy of tropical cyclones are primarily from their underlying boundary layer (e.g., Emanuel...
1986; Betts and Simpson 1987). Modification of the tropical cyclone boundary layer by moist convection associated with TCRs may thus have an important impact on the subsequent development of tropical cyclones (e.g., Powell 1990a,b). With advances in aircraft instrumentation technology since the 1970s (Jorgensen 1984), the mesoscale structures of TCRs in terms of their associated precipitation, airflow, and thermodynamics have been revealed (e.g., Barnes and Stossmeister 1986; Ryan et al. 1992; Samsury and Zipser 1995; Hence and Houze 2008). However, little has been learned about the surface features of TCRs from these aircraft investigations because of the inherent limitation of aircraft flight-level measurements, usually confined to altitudes above at least 150–500 m MSL.

The earliest documentation of the surface features of TCRs can be found in the literature from the 1950s and 1960s. Using radar images and surface observations, a few observational studies have described how surface meteorological variables change as landfalling TCRs pass by (e.g., Ligda 1955; Ushijima 1958; Hamuro et al. 1969). These preliminary findings include a dip in surface pressure, a clockwise shift in wind direction, and a general decrease (increase) in temperature (humidity). Owing to the limitation of rather coarse temporal and spatial resolution of radar and surface measurements, these earlier studies provided only very limited, gross pictures of surface fluctuations during the passage of TCRs.

A more quantitative depiction of surface features of TCRs was provided from a recent study by Skwira et al. (2005). They used surface tower and radar observations collected as part of the Wind Engineering Mobile Instrumented Tower Experiment (WEMITE) to investigate the surface characteristics of inflow and equivalent potential temperature associated with several TCRs making landfall on the Atlantic coast of the United States. Their analyses indicate that the observed TCRs possessed a considerable deficit in equivalent potential temperature (\(\sim 3–10 \text{ K}\)) and variable intensities of storm-relative inflow were observed within different TCRs. Since the TCRs examined by Skwira et al. (2005) were predominantly characterized by stratiform precipitation, the surface features of TCRs presented by the study would be much less representative of convectively active TCRs commonly observed (e.g., Barnes et al. 1983).

More recently, Yu and Tsai (2010, hereafter YT) used temporally high-resolution surface and radar observations to document the finescale features of two well-defined, convectively active TCRs as they passed over northern Taiwan. Their analyses show a wavelike pressure perturbation characterizing the studied TCRs, with a low (high) pressure located inside their outer (inner) edge. Maximum (minimum) pressure perturbations were observed to be approximately 1.5 (1) mb, with smaller magnitudes (\(<-0.4 \text{ mb}\)) outside the outer (inner) edge. The detailed diagnoses from the study further suggest that the pressure perturbations produced by moist convection and those associated with gravity wave–like fluctuations initiated near the inner core of the tropical cyclone were both important in contributing to the observed surface pressure features.

Based on case studies from a very limited number of previously documented TCRs, it is clear that our understanding of the general surface features of TCRs is rather incomplete. The objective of this study is to use temporally high-resolution surface observations to investigate surface fluctuations associated with TCRs as they approached or passed over the Taiwan area during 2000–08. Taiwan is a well-known target for tropical cyclones originating over the northwestern Pacific Ocean. On average, there are 3–4 typhoons impacting Taiwan every year (Wu and Kuo 1999). With the advantage of the whole-island Doppler radar observing network established by the Central Weather Bureau (CWB) of Taiwan in 2000, identifying a significant number of TCRs through long-term radar observations became possible. This valuable TCR database encompassing a 9-yr period from 2000 to 2008 allows a more comprehensive and unique documentation of TCR surface features. The particular attempt of this study is to understand the main features and possible diversity of TCR surface fluctuations. The implications of these observations on the dynamic and convective nature of TCRs and their potential role in modifying the tropical cyclone boundary layer are also discussed.

2. Data and identification of TCRs

The datasets used in this study to investigate TCRs include surface and Doppler radar observations and are summarized in Fig. 1. Measurements from the CWB operational S-band (10 cm) Doppler radars [Weather Surveillance Radar-1988 Doppler (WSR-88D)] at Wufen-San (WFS), Chi-Gu (CG), and Ken-Ting (KT) were used to provide the detailed precipitation information associated with typhoons as they approached Taiwan. The radars have volumetric distributions of reflectivity with a temporal interval of approximately 6 min between each volume and a maximum observational range of 230 km (Yu and Cheng 2008). The data coverage of these three Doppler radars encompasses extensive regions over the entire Taiwan landmass and its coastal vicinity from nearshore to 150–200 km offshore (Fig. 2). Low-level plan position indicator (PPI) scans (0.4° and/or 1.4° elevations) of reflectivity from these radars were
first generated from all typhoon events during 2000–08 whose warning reports were issued by CWB. To find TCRs approaching Taiwan, horizontal precipitation patterns associated with typhoons were checked subjectively by screening this large set of PPI scans. Identification of a TCR for the present study was based on the following criteria. An organized feature of radar-observed reflectivity with relatively stronger (weaker) precipitation intensity inside (outside) the band, with a length much greater than its width, must be visually seen. Also, reflectivity values along the bands should be greater than 20 dBZ and the boundary of the bands must be well determined via horizontal reflectivity patterns. These two criteria could effectively avoid including those precipitation features with relatively transient showers or light stratiform precipitation usually present within typhoons. Moreover, the criteria above must hold valid while the precipitation bands pass over the surface stations. Locations of the surface stations selected for this study are indicated in Fig. 1. With comprehensive examination of available radar measurements from 2000 to 2008, a total of 263 TCRs satisfying the above criteria were identified from 37 typhoon events. Table 1 summarizes the studied typhoons and their corresponding number of rainbands. The typhoon intensity indicated in Table 1 was determined at a time closest to the passage of TCRs over surface stations. More than half of the TCRs (142) were observed within typhoons with moderate intensity. Far fewer numbers of TCRs (35) were identified within weak typhoons because of the less organized nature of convection inside them. The number of TCR passages over each of the selected surface stations during the study period and the best track of the studied typhoons from CWB are also shown in Figs. 1 and 2, respectively.

Given a generally westward movement for northwestern Pacific typhoons (cf. Fig. 2), the influence of Taiwan topography resulted in far fewer identified TCRs in the wake of the Taiwan landmass (i.e., the western portion of Taiwan) (Fig. 1). Note that the TCRs identified along the coast of southwestern Taiwan were associated with those typhoons with tracks passing over farther offshore regions. These typhoon rainbands propagated mostly northeastward and made landfall on the southwestern coast. Therefore, these rainbands had not been impacted significantly by Taiwan topography as they passed over the surface stations of southwestern Taiwan. It is possible that a given TCR, as it advances over the Taiwan area, may pass over several surface stations. In such a case, only observations from one particular surface station, where the TCR can be best identified and is found to possess a more transverse passage,1 were taken into account and chosen for analysis in the present study. Hence, the number of TCR passages indicated at each station (Fig. 1) represents the real case number of the identified TCRs.

A plan view of all identified TCRs with respect to the typhoon center and the direction of typhoon motion is illustrated in Fig. 3. A diverse distribution of the identified TCRs was seen, with radial distances ranging from about 50 to 600 km. The majority of the TCRs were confined to the front quadrants and relatively fewer TCRs (~20%) identified were located within the rear quadrants. This asymmetric distribution of TCRs was primarily due to the influences of topography for typhoons approaching or encountering Taiwan, although the movement of the tropical cyclone and the vertical shear of the large-scale environment are also potential contributors to this asymmetry (Houze 2010). According to Wang (2009), the rainband’s position within (beyond) a radius of 2–3 times the radius of maximum wind (RMW) can be dynamically classified into the inner (outer) rainband. Given the RMW of typhoons usually

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1 The meteorological variations in a direction normal to the typhoon rainband are the focus of this study, and choosing surface observations from a more transverse passage could minimize the signals due to along-band variability.
between 10 and 100 km (Anthes 1982; Houze 2010), the two rainband types, “inner TCRs” and “outer TCRs”, are expected to both be included in our analyzed TCR database. Scientific issues concerning the outer and inner rainbands will be elaborated in later sections.

Finescale surface fluctuations of TCRs presented in this study were primarily revealed by the time series analyses of 1-min temporal resolution surface observations during the passage of the TCRs. The normal-band extent of a TCR can be practically considered as a region of enhanced precipitation bounded by the outer and inner edges of the rainband. A reflectivity threshold of 25 dB
\[ Z \]
has been commonly adapted to delineate the edges of TCRs (e.g., Jorgensen and Willis 1982; Barnes et al. 1983; Barnes and Stossmeister 1986). The 25-dB
\[ Z \] threshold can effectively eliminate more transient radar echoes and/or light stratiform precipitation but retain the moderate stratiform precipitation associated with TCRs (Barnes et al. 1983). Since some variability of precipitation intensity associated with the TCRs was found for the present study, the reflectivity criterion used to locate the TCR’s edges was raised from 20 to 35 dB
\[ Z \] with a 5-dB
\[ Z \] interval to provide a better definition of the TCR’s envelope. Because of the prevalence of convective precipitation for the identified TCRs, their edges were typically characterized by an obvious horizontal gradient of reflectivity values. Therefore, the different reflectivity thresholds used herein were just for a practical need of locating TCRs and should not have a strong impact on the relevant analyses presented in the following sections. A sample plot to illustrate the horizontal reflectivity pattern of our identified TCRs is shown in Fig. 4.

3. Composite features

To obtain the representative surface features associated with the identified TCRs, a spatial composite of perturbation fields was first performed with respect to the width of each rainband (i.e., the distance between the outer and inner edge) as it passed over the surface stations. The axis of the rainband is considered the central point between the outer and inner edge (Fig. 4). The perturbation value in this study is defined as a departure between the observed value and the mean value averaged within the outer/inner edge. Ten surface meteorological

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**Fig. 2.** Best track of 37 typhoons selected for the present study of TCRs from the Central Weather Bureau of Taiwan. Typhoon center is indicated every 6 h. Black triangles denote the location of three Doppler radars and heavy dashed circles indicate their corresponding observational range (230 km).
quantities—temperature $T$, dewpoint temperature $T_d$, relative humidity (RH), pressure $p$, equivalent potential temperature $\theta_e$, cross-band $V_c$ and along-band $V_a$ wind components, wind speed $W$, and direction $W_d$—were analyzed in the composite. To isolate pressure fluctuations caused by the passage of the TCRs, the changes in pressure due to the approach/ departure of the storm-scale typhoon depression must be removed. Since the typical duration for the passage of individual typhoon rainbands at a given surface station was observed to be less than 60 min, the 1-h running mean of surface pressure measured from the surface station was adopted to remove the band-scale pressure fluctuations. The pressure values associated with TCRs were first obtained by subtracting the above-calculated mean pressure (which represents the storm-scale pressure tendency) from the pressure values recorded at a given station and time, and the perturbation pressure used for the composite was then calculated from these newly derived pressure values. The procedures for calculating perturbation pressure herein are the same as those described in YT.

Both $V_c$ and $V_a$ were calculated from surface-measured winds based on the local orientation of the TCRs near the location of the surface station that they passed over (cf. Fig. 4). The relative flow field normal to the rainband (i.e., the band-relative cross-band wind component) was determined by taking into account the propagation speed of the band. No attempt was made in this study to calculate the relative along-band wind component because of the difficulty in estimating the along-band propagation motion of rainbands. Given a typical transverse passage of the identified TCRs as described earlier, this uncertainty, however, should not be significant. The propagation speed for the identified TCRs was estimated by subjectively tracking their outer edge when it passed over the surface stations. A dominant portion of the identified TCRs ($\approx 92\%$) exhibited a propagation speed ranging from 4 to 20 m s$^{-1}$; the mean propagation speed calculated from all identified TCRs was approximately 11 m s$^{-1}$.

Figure 5 shows the composite results of various surface thermodynamic and kinematic perturbations accompanying the identified TCRs. For a clearer illustration of the surface fluctuations within the rainband and its immediate environment, the spatial composite was extended to the half-width of each rainband beyond its outer/inner edge. Values of composite perturbations were relatively...
small compared to those seen from individual rainbands primarily because of the natural variability of fluctuations associated with different TCRs. According to the two-tailed Student’s $t$ test, the critical magnitudes for $p'$ (0.04 mb), $T'$ (0.06°C), $T_d'$ (0.06°C), $\theta_e'$ (0.24 K), RH' (0.25%), $W'_d$ (0.24 m s$^{-1}$), $W'_d$ (1.7°C), $V'_d$ (0.28 m s$^{-1}$), and $V'_d$ (0.24 m s$^{-1}$) could be statistically considered to be significantly different from zero perturbation at the 95% level. The patterns of composite fluctuations exhibit maximum/minimum values generally well above these critical magnitudes. Figure 5 indicates that the primary variation of the perturbation fields occurred within the rainband. There was an obvious, persistent decrease in temperature, dewpoint temperature, and equivalent potential temperature from the outer to inner edge; however, the decreasing tendency of dewpoint temperature was relatively minor compared to the other two. Given a typically unsaturated condition for the subcloud regions of the rainband (not shown), the decreasing trend of temperature inside the rainband was consistent with the evaporative influences of precipitation particles.

It is interesting that relative humidity became higher near the axis and inside the inner edge, implying the reduction in saturated water vapor pressure due to evaporative cooling (i.e., lower temperature) overwhelmed the decrease in water vapor pressure (i.e., lower dewpoint temperature). The decrease of the absolute moisture amount evident within the rainband would suggest the importance of the downward transport of drier air originating from higher altitudes by convectively induced downdrafts (e.g., Barnes et al. 1983; Skwira et al. 2005). This process has also been shown to commonly occur for tropical deep convection, contributing to the development of a boundary layer cold pool with negative perturbations of both temperature and water vapor fields (e.g., Tompkins 2001).

Relatively low (high) pressure was present on the outer (inner) side, with a minimum coincident with the outer edge and a maximum located inside the inner edge. Particularly, a clear undulation of pressure perturbations associated with the rainband was evident. The wavelike fluctuations support the recent findings from a detailed case study of landfalling typhoon rainbands by YT, who documented rather similar variations of surface pressure for their studied rainbands. In addition, the composite pressure perturbations shown in Fig. 5 indicate that the pressure ridge tended to occur

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2 The two TCRs examined in YT were also included in this study. The composite features remain unchanged even when we remove the YT rainbands from our TCR database.
inside the inner edge of the rainband. This feature, however, was somewhat different from the previously proposed conceptual pattern of pressure perturbations associated with the passage of TCRs [cf. Fig. 2.18b in Anthes (1982)], which shows the coincidence of the pressure ridge with the inner edge when considering the TCRs as a manifestation of pure gravity wave disturbances. Such a difference in pressure signature should not be surprising since the influences of pressure perturbations generated by moist convection associated with TCRs may play a role in this respect, as demonstrated by YT.

The composite kinematics for the identified TCRs (Fig. 5) was characterized by an obvious decrease in cross-band wind component with positive (negative) perturbations on the outer (inner) side. There was an increase in along-band wind component within the rainband, but the variation was slight compared to the cross-band wind component. The maximum wind speed was found on the inner side, immediately adjacent to the inner edge. This feature is the opposite of the aircraft observations of the outer hurricane rainbands presented in Powell (1990a), which show along-band and cross-band wind maxima on the outer side of the band axis. For the present case, the combination of typhoon-scale mean cyclonic circulations with generally anticyclonic vorticity seen from the cross-band variation of along-band winds (cf. Fig. 5), however, is consistent with the occurrence of maximum wind speed on the inner side of the rainband. Negative-to-positive perturbations of wind direction from the outer-to-inner edge indicate the wind veering during the passage of the rainband (Fig. 5), consistent with the confluence of surface flow

Fig. 5. Composite surface features of all identified TCRs for various meteorological variables ($T'$, $T_d'$, RH', $P'$, $\theta_e'$, $V_c'$, $V_a'$, $W_s'$, $W_d'$, and RR). The outer and inner edges of the rainband located at $X = -0.5$ and $X = 0.5$ are denoted by vertical dashed lines, and the axis of the rainband ($X = 0$) is denoted by the vertical solid line.
into the rainband (Anthes 1982). More intense rainfall rates occurred inside the inner edge, with a maximum of approximately 20 mm h\(^{-1}\). In the rainband, the heaviest rain was roughly collocated with the peak of surface high pressure, although the region of strongest wind and rainfall did not appear coincident.

Qualitatively, some of the surface fluctuations seen in Fig. 5 are in agreement with those observed by previous investigations of TCRs, but observations from the study provide more complete information for the connection among perturbations of various meteorological variables in the vicinity of the TCRs. These observed trends have not been revealed or addressed by previous case studies of TCRs. Quantitative aspects of TCR fluctuations will be presented in the next section.

4. Quantitative analysis of fluctuations

In this section, a quantitative perspective of surface features for the identified TCRs is provided by analyzing the magnitude of surface fluctuations during the passage of the rainbands. The magnitude of fluctuations for a given meteorological variable (except for the rainfall rate) in this study is defined as a difference between the maximum and minimum value found within the outer/inner edge of the rainbands. Because surface variations in the vicinity of the identified TCRs occurred primarily inside the rainband (cf. Fig. 5), the magnitude as calculated above could well represent the “amplitude” of TCR fluctuations. It could also be regarded as a reasonable measure for the degree of boundary layer modifications by the rainband’s convection.

Mean and maximum values, as well as standard deviation, for the magnitudes of surface fluctuations for all TCRs identified in this study are summarized in Table 2. For a better illustration of the fluctuation distribution, their corresponding accumulative frequency is also shown in Fig. 6. The discussion below not only reflects some limited knowledge of the near-surface features of TCRs learned from previous observational studies of TCRs, but also provides further details about the natural variability of their associated surface characteristics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Max</th>
<th>Std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta P) (mb)</td>
<td>0.9</td>
<td>7.8</td>
<td>0.8</td>
</tr>
<tr>
<td>(\Delta T) (°C)</td>
<td>0.8</td>
<td>4.0</td>
<td>0.9</td>
</tr>
<tr>
<td>(\Delta T_d) (°C)</td>
<td>0.9</td>
<td>3.8</td>
<td>1.5</td>
</tr>
<tr>
<td>(\Delta \theta_v) (K)</td>
<td>4.0</td>
<td>15.0</td>
<td>3.4</td>
</tr>
<tr>
<td>(\Delta RH) (%)</td>
<td>3.9</td>
<td>31.0</td>
<td>4.0</td>
</tr>
<tr>
<td>(\Delta W_u) (m s(^{-1}))</td>
<td>3.7</td>
<td>17.5</td>
<td>3.4</td>
</tr>
<tr>
<td>(\Delta W_d) (°)</td>
<td>17.8</td>
<td>160.0</td>
<td>24.1</td>
</tr>
<tr>
<td>(\Delta V_e) (m s(^{-1}))</td>
<td>4.1</td>
<td>18.6</td>
<td>24.1</td>
</tr>
<tr>
<td>(\Delta V_a) (m s(^{-1}))</td>
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<td>21.3</td>
<td>3.7</td>
</tr>
<tr>
<td>Max RR (mm h(^{-1}))</td>
<td>3.7</td>
<td>225.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The majority of the TCRs (~80%) exhibited fluctuations in wind speed and direction less than 5 m s\(^{-1}\) and 20°, respectively. The mean fluctuation of the cross-band wind component (4.1 m s\(^{-1}\)) was slightly more pronounced than that of the along-band wind component (3.7 m s\(^{-1}\)), basically consistent with the composite results (cf. Fig. 5) showing relatively minor variations of the along-band wind component across the rainband.

There was a tendency for large standard deviations of surface fluctuations with values close to the mean value of each meteorological variable indicated in Table 2. This result, together with the statistical frequency distributions shown in Fig. 6, implies a generally diverse nature of surface characteristics associated with TCRs. An interesting and important question arising from this statistical characteristic concerns whether variable magnitudes of surface fluctuations seen from different TCRs are strongly dependent on their radial distance with respect to the typhoon center. As proposed by previous theoretical and modeling studies of tropical cyclones, the behavior of TCRs would be ultimately determined by the degree to which they are influenced by the inner-core.
FIG. 6. Accumulative frequency distribution for magnitudes of various surface fluctuations associated with TCRs [perturbation pressure $\Delta P'$, temperature $\Delta T$, dewpoint temperature $\Delta T_d$, equivalent potential temperature $\Delta \Theta_e$, relative humidity ($\Delta RH$), wind speed $\Delta W_s$, wind direction $\Delta W_d$, cross-band flow $\Delta V_c$, along-band flow $\Delta V_a$, and maximum rainfall rate (max RR)].
vortex dynamics of the cyclone (Diercks and Anthes 1976; Kurihara 1976; Willoughby 1977; Montgomery and Kallenbach 1997). The so-called outer (inner) TCRs located outside (inside) the radius of the inner-core environment are weakly (strongly) constrained by the dynamics of the inner-core vortex (e.g., Wang 2008). However, the distinction between the outer and inner TCRs in terms of their surface features is still rather ambiguous at this stage because of the lack of detailed information about the continuous spectrum of TCRs from real observations. Moreover, while the potential importance of moist convection associated with TCRs influencing the intensity of tropical cyclones has long been recognized (e.g., Willoughby et al. 1982; Wang 2009), the relative contribution of the outer and inner TCRs to the modification of the tropical cyclone boundary layer has not been addressed explicitly by either observational or modeling studies of TCRs and thus remains quite ambiguous.

In an attempt to clarify these aforementioned aspects, the magnitudes of surface fluctuations for all identified TCRs in this study were further analyzed as a function of radial distance with respect to the typhoon center. In this analysis, the representative magnitude of surface fluctuations at a given radial distance was obtained by taking the mathematical average for those TCRs located within a radial ring of 40 km. The averaging procedure allows a clearer depiction of the trend of radial variation of the TCR’s surface fluctuations. Note that an alternative way to obtain the radial trends may be provided by fitting a polynomial least squares curve to the available data points. It was found that the trends revealed by the curve fitting were basically consistent with those derived from the simple averaging procedure applied herein.

The radial variations of thermodynamic and kinematic fluctuations are illustrated in Fig. 7. The range of mean values at the 90% confidence level was also superposed on Fig. 7 to show the statistical uncertainties for the averaging procedure. Beyond a radial distance of about 400 km, the data points within each of the calculated intervals (i.e., the 40-km radial ring) were much fewer (<10), resulting in relatively larger uncertainties of the calculated mean values over these far outer regions. It is evident that the magnitudes of temperature and moisture fluctuations (Figs. 7b,c,e) exhibited a consistent increase with radial distance. An obvious radial variation in the fluctuations of equivalent potential temperature was also observed, increasing from about 3 K in the near-core region (within the radial distance of 150 km) to about 9 K at the far outer regions of tropical cyclones (Fig. 7d). Unlike the significant radial variations in thermodynamic fluctuations, the magnitudes of surface pressure fluctuations remained essentially unchanged within a radial distance of about 200 km, with a trend of slight decrease beyond that (Fig. 7a). The observed inconsistent trend of radial variations between the pressure and thermodynamic fields implies that the pressure perturbations of the TCRs were not dominantly governed by convective diabatic effects (e.g., YT). Radial variations for the kinematic fluctuations (Figs. 7f–i) were overall much weaker compared to thermodynamic fluctuations, with some suggestion of slightly larger fluctuations in wind direction at the far outer regions. The maximum surface rainfall rates tended to sustain a nearly constant intensity (~40–50 mm h⁻¹) from the inner core to the outer regions of the tropical cyclone (Fig. 7j). The peak of surface rainfall rate (~100 mm h⁻¹) found near the radial distance of 450 km may be less representative because of relatively fewer TCRs identified in these far outer regions (cf. Fig. 3).

The analyses above indicate a generally fundamental dependence of the TCR’s surface fluctuations (particularly for the thermodynamic field) on the radial distance from the typhoon center. This observational finding and its relevant implications will be further elucidated in the next section.

5. Outer versus inner rainbands

a. Determination and composite

To provide some physical insight for the variable magnitudes of the TCR’s surface fluctuations over different radial distances from the typhoon center, the TCRs identified in this study were classified into the outer and inner rainbands and a composite procedure similar to that described in section 3 was then applied to obtain the mean fluctuations for these two types of rainbands. A radial distance of 3 times the RMW, as proposed by Wang (2009), was employed as an approximate radius threshold for the rainband’s classification. In the analysis, the RMW estimate (e.g., Knaff et al. 2007; Kossin et al. 2007) for each studied typhoon was provided by the Joint Typhoon Warning Center (JTWC). Since the magnitude of the RMW usually varied with time as the typhoons evolved, a representative RMW from a time closest to the passage of TCRs over surface stations was chosen for each identified TCR. The RMW information became more complete after 2004 from the JTWC tropical cyclone best-track archive (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/) and hence some of the identified TCRs observed before 2003 (Table 1) were disregarded in the composite analysis. The available RMWs (~80% of the identified TCRs) from JTWC were found to range from about 20 to about 85 km, with a mean value of 37 km.

Similar to the illustration of Fig. 3, the plan view of the outer and inner TCRs with respect to the typhoon center
is shown in Fig. 8. A total of 157 (53) TCRs were classified as the outer (inner) rainbands, and a dominant portion of the inner TCRs was confined to the vortex core region, within 150 km of the storm center. Note that there were 53 unclassified TCRs due to the lack of available RMW information for the typhoons associated with these rainbands. Only a small number of these unclassified rainbands (open circles in Fig. 8) were located within 3 times the averaged RMW (∼110 km), suggesting that the majority of them would belong to the outer rainbands.

The composite features of the outer and inner rainbands revealed some important characteristics. The outer band possessed obvious thermodynamic fluctuations in temperature, dewpoint temperature, and relative humidity...
In particular, a pronounced decrease in the equivalent potential temperature was found across the rainband, although the low values of $u_e$ appeared to be restored slightly outside the inner edge of the band. Temperature and moisture fluctuations within the inner rainband were relatively small (Fig. 10). A slight increase in dewpoint temperature was observed inside and near the inner edge, an observational characteristic distinctly different from that seen in the composite of all identified TCRs (Fig. 5) and the outer rainband (Fig. 9).

A clear high–low pressure couplet was associated with the outer band, which is rather similar to the composite pressure features for all identified TCRs shown in Fig. 5. In contrast, the inner band was characterized by multiple, smaller-amplitude undulations of pressure perturbations. The pressure minimum was evident near its outer edge; however, unlike the outer band, the pressure maximum was located inside the outer edge and associated with relatively lower rain rates. Convective effects such as water loading and subcloud evaporation did not seem to play a dominant role in generating the observed pressure maximum on the inner side of the outer edge because the location of the pressure maximum was associated with relatively weaker precipitation and nearly zero temperature variations (Fig. 10). However, several local peaks of pressure perturbations seen in the composite corresponding roughly to relative maxima of rainfall rates indicate water loading as a potential contributor in influencing the pressure distribution inside the inner band.

Differences in kinematic and precipitation fluctuations between the outer and inner band were less significant compared to the thermodynamic fields. One might note that a localized maximum of wind speed was evident inside the inner edge of both the outer and inner band (Figs. 9 and 10); however, the wind speed and the along-band flow for the inner band tended to increase continuously even outside the inner edge, consistent with the Rankine-vortex wind profile typical within the inner core region of tropical cyclones.

More pronounced thermodynamic variations associated with the outer band, as seen from the composite results discussed above, can be further validated by calculating the mean magnitudes of surface fluctuations for the two classified groups of rainbands (i.e., the outer and inner TCRs) (Table 3). Statistical significance for the difference in mean values of the two rainband groups subjected to a Student’s $t$ test is also indicated in Table 3. It is clear that larger mean magnitudes of fluctuations in temperature, dewpoint temperature, equivalent potential temperature, and relative humidity were observed within the outer band. In contrast, statistically there were no significant differences in kinematic variations between the outer and inner band, as revealed by their almost equal mean values and the acceptance of the two null hypotheses made herein. The means of maximum rainfall rate for the outer and inner bands were also quite comparable. These calculated results are basically in good agreement with the radial trends as shown in Fig. 7.

b. Discussion

There are several important implications from the analysis results above. First, it is clear that the outer rainbands appear to have a higher potential than the inner rainband to modify the tropical cyclone boundary layer through reducing the near-surface $u_e$ values. Maintaining surface $u_e$ of inflowing air to values high enough to support the development of moist convection has been long believed to be one of the key processes in increasing tropical cyclone intensity (e.g., Malkus and Riehl 1960; Emanuel 1986; Betts and Simpson 1987). In this context, the horizontal extent and distribution of the outer bands (instead of the inner bands) within tropical cyclones and the efficiency for the recovery of lower-$u_e$ air while it spirals into the inner core region are expected to be crucial factors in altering the supply of convective energy to the storm intensity. It should be also noted that although from the “thermodynamic modification of the boundary layer by moist convection” point of view, the inner bands tend to play a relatively minor role, their
impact on the development of the eyewall and the intensification of tropical cyclones has recently received increased attention. A typical scenario concerns the concentric eyewalls and their subsequent replacement processes (Willoughby et al. 1982; Black and Willoughby 1992; Houze et al. 2007; Kuo et al. 2009). Nevertheless, the dynamical aspects of the outer eyewall formation and the processes for how it and/or the inner bands contribute to the collapse of the inner eyewall are still controversial (e.g., Rozoff et al. 2008; Judt and Chen 2010; Kieu and Zhang 2010; Qiu et al. 2010).

To identify physical causes for the contrasting $\theta_e$ variation between the outer and inner bands observed herein is beyond the scope of the study, but it could be closely related to the ambient thermodynamic conditions and convective structures of TCRs (e.g., Frank 1977; Powell 1990b; Bogner et al. 2000). For example, the outer rainband’s environment observed in this study was generally characterized by relatively drier atmospheric conditions, as revealed by the mean surface relative humidity prior to the passage of the rainbands (observed to be 91% and 95% for the outer and inner TCRs, respectively). More significant evaporative cooling of precipitation particles may occur in the subcloud region of the outer TCRs, consistent with a more prominent drop in surface temperature inside the rainband (cf. Fig. 9). However, a more notable decrease in dewpoint temperature within the outer rainband cannot be attributed to the evaporative processes that are expected to increase moisture. Instead, the feature would more probably result from the downward transport of lower-$\theta_e$ air aloft by convective downdrafts within the...

![Diagram](http://journals.ametsoc.org/jas/article-pdf/68/8/1568/3532728/2011jas3725_1.pdf)
rainband, as described in section 3. The combined effects of both evaporative cooling and the downward transport of elevated drier air are required to explain the decrease of both near-surface temperature and water vapor for the outer TCRs (e.g., Tompkins 2001). Given that a typical typhoon environment in the lower troposphere is characterized by convective instability (i.e., $\theta_e$ decreases with height) (Sheets 1969; Eastin et al. 2005),

| TABLE 3. Mean and standard deviation of magnitudes of various surface fluctuations calculated from the two classified groups of rainbands (i.e., the outer and inner band). The statistical significance testing for the difference in the mean values of the two groups of rainbands is also indicated. The first null hypothesis $H_{01}$ is that the mean is equal for the two groups, and the second null hypothesis $H_{02}$ is that the mean of the outer band is smaller than or equal to the mean of the inner band. The letter A (R) denotes null hypotheses being accepted (rejected); $H_{01}$ ($H_{02}$) is rejected at the 0.05 (0.01) level of significance. |
|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $\Delta \rho$ (mb) | $\Delta T$ (°C) | $\Delta T_d$ (°C) | $\Delta \theta_e$ (K) | $\Delta RH$ (%) | $\Delta W_e$ (m s$^{-1}$) | $\Delta W_d$ (°) | $\Delta V_e$ (m s$^{-1}$) | $\Delta V_d$ (m s$^{-1}$) | max RR |
| Mean (outer) | 1.0 | 0.8 | 0.9 | 4.1 | 3.9 | 3.6 | 15.9 | 4.1 | 3.7 | 40.4 |
| Mean (inner) | 0.8 | 0.5 | 0.6 | 2.9 | 2.3 | 3.4 | 16.0 | 3.7 | 3.5 | 41.0 |
| Std dev (outer) | 0.9 | 0.9 | 0.8 | 3.5 | 3.5 | 3.1 | 21.1 | 3.6 | 2.9 | 39.0 |
| Std dev (inner) | 0.6 | 0.4 | 0.4 | 2.1 | 1.9 | 2.2 | 23.8 | 3.3 | 3.1 | 37.4 |
| $H_{01}$ | A | R | R | R | R | A | A | A | A |
| $H_{02}$ | A | R | R | R | R | A | A | A | A |
it is thus reasonable to suspect that the convective downdrafts produced within the outer TCRs would be more prevalent and vigorous than the inner TCRs. This speculation is supported by the observational fact that the convective elements in the outer TCRs can sometimes develop arc-shaped radar echoes, a signature that suggests the occurrence of strong downdrafts spreading out near the surface (e.g., Houze 2010). In contrast, slightly higher moisture and lower temperature associated with the inner TCRs (Fig. 10) are consistent with the dominance of relatively weak evaporation taking place in subcloud regions.

As demonstrated by a considerable number of tropical cyclone studies, the outer TCRs have been dynamically interpreted as the manifestations of atmospheric inertia–gravity waves (e.g., Diercks and Anthes 1976; Kurihara 1976; Willoughby 1977), whereas the inner TCRs have been recently recognized to be probably related to vortex Rossby waves (e.g., Montgomery and Kallenbach 1997).

In addition to the significance of the aforementioned wave dynamics, boundary layer instabilities have also been proposed to explain the formation and propagation of TCRs (e.g., Faller 1961; Fung 1977). Owing to the lack of adequate observational validation for these previous theoretical modeling works, the specific processes contributing to the initiation of TCRs are still far from definitive. Despite these uncertainties, the occurrence of atmospheric gravity waves usually can be practically identified from the temporal and spatial variations of the surface pressure field (e.g., Uccellini 1975; Miller and Sanders 1980; Einaudi et al. 1987; Savage et al. 1988). Particularly, evidence from a number of previous studies of convective storms and TCRs has shown the high–low pressure couplet as the most striking surface signature associated with the propagating gravity wave–like disturbances (e.g., Anthes 1982; Koch and Golus 1988; Yang and Houze 1995; YT).

For the present case, a highly similar pressure undulation (i.e., the high–low pressure couplet) was evident for the outer rainband (Fig. 9). Its associated pressure maximum collocated with the region of highest rain rates was also consistent with the characteristics of atmospheric gravity waves that typically exhibit maximum cloudiness and precipitation near their wave pressure ridge (e.g., Eom 1975; Uccellini 1975; Koch and Golus 1988). However, one might suspect that positive pressure perturbations produced by the evaporative and water loading effects may contribute in part to the high pressure observed inside the inner edge of the outer band (YT). Lack of a well-defined high–low pressure couplet for the inner rainband (Fig. 10) suggests, however, that it would be less relevant to the gravity wave–induced perturbations. It is possible that more complicated variations of surface pressure fluctuations seen from the inner rainband are related to the perturbations of other wave types and/or are influenced by some combined effects of moist convection and boundary layer processes.

It is difficult, based on our surface observations alone, to explicitly address whether the behavior of the inner rainband resembles vortex Rossby waves. When considering the inner rainband as a manifestation of vortex Rossby waves, the occurrence of moist convection associated with the band may be understood as a consequence of the triggering of the boundary layer upward motion produced by the interaction of the potential vorticity anomalies with surface friction (e.g., Chen and Yau 2001). In this context, the rainband is expected to be characterized by enhanced cyclonic vorticity and frictionally induced upward motion. For the present study, the contribution of frictional convergence to the vertical velocity at the top of the boundary layer $W_t$, vertical vorticity $\zeta$, and horizontal divergence $D$ may be approximated by

$$ W_t = \frac{1}{\rho f} \frac{\partial}{\partial x} \left( \rho C_d V_v V_a \right) - \frac{\partial}{\partial y} \left( \rho C_d V_v V_a \right), $$

$$ \zeta = \frac{\partial V_v}{\partial x} - \frac{\partial V_a}{\partial y}, $$

$$ D = \frac{\partial V_a}{\partial x} + \frac{\partial V_v}{\partial y}, $$

where $\rho$ is the air density, $f$ is the Coriolis parameter, $C_d$ is the drag coefficient, $V_v$ is the wind speed, and $x$ and $y$ are respectively the cross-band and along-band directions. The expression of (1) follows Bond and Fleagle (1985) and is derived from a vorticity equation for the boundary layer (e.g., Fleagle et al. 1988). In synoptic situations, this term is often referred to as Ekman pumping (Fleagle and Nuss 1985). We can estimate $C_d$ by using the formulation described in Large and Pond (1982). Given a typically two-dimensional reflectivity pattern for the identified TCRs (cf. Fig. 4), the along-band variability of winds in (1)–(3) is assumed minor and is thus ignored. Moreover, a space–time transformation of surface–observed quantities based on the estimated propagation speed of the rainbands is also required for calculating the spatial derivatives in (1)–(3). With the potential uncertainty arising from the relevant assumptions and estimations, the attempt herein is just to explore if there is any fundamental difference in the mean dynamical characteristic between the outer and inner rainbands. Hence, the values of frictional velocity, vertical vorticity, and divergence calculated inside the rainband’s outer/inner edge are simply averaged for all classified outer and inner rainbands, respectively. The results are indicated
in Table 4. It is evident that the outer band exhibits negative frictional vertical velocity and stronger convergence; because it is associated with negative vorticity, the presence of the near-surface convergence should not be directly related to the forcing of surface friction. In contrast, the inner band is found to possess obvious cyclonic vorticity and frictional upward motion, similar to the near-surface features of a vortex Rossby wave–like disturbance (Chen and Yau 2001). Although these results may not firmly validate the importance of Rossby wave dynamics to the formation of the inner rainbands, they at least reflect a possibly different origin for the outer and inner rainbands, consistent with the contrasting signatures of their associated surface pressure fluctuations seen in Figs. 9 and 10.

Finally, it is important to note that, because the outer TCRs are located far enough from the vortex center, they are relatively free of the constraints of the inner-core vortex dynamics and would mostly behave like ordinarily organized convective systems, such as squall lines (Willoughby 1988; Houze 2010). In contrast, the moist convection associated with the inner TCRs would more probably possess some unique convective features tied to the vortex dynamics, in a manner similar to the principal rainband or secondary rainbands of tropical cyclones3 (Barnes et al. 1983; Hence and Houze 2008; Houze 2010). From this standpoint, we expect to see more pronounced surface fluctuations in the outer TCRs than in the inner TCRs, regardless of the thermodynamic or kinematic fields. Obviously, this is not entirely the truth. The observed larger thermodynamic fluctuations characterizing the outer TCRs, as discussed earlier, may be interpreted as a convective behavior toward the squall-line-like precipitation system; however, a minor difference in kinematic fluctuations between the outer and inner TCRs (Figs. 9 and 10; Table 3) and relatively weak radial variations in magnitudes of their kinematic fluctuations (Figs. 7f–i) did not suggest an entirely clear distinction between the outer and inner TCRs. Therefore, it is likely that the outer TCRs may take on some sort of mixture of ordinary deep convection and moist convection induced purely by the dynamics of the inner-core vortex. Future detailed observations collected from a wide variety of TCRs located at different radial distances and encompassing both the inner core and outer regions of tropical cyclones will be required to further validate the differences in convective nature between the outer and inner rainbands.

### 6. Conclusions

In this study, temporally high-resolution surface observations have been used to investigate the finescale surface features for 263 tropical cyclone rainbands (TCRs) identified from the long-term radar measurements during 2000–08. The identified TCRs were from 37 typhoons approaching or making landfall on Taiwan and they were distributed over a wide range of radial distances from about 50 to 600 km. A significant amount of TCRs from this study provided more comprehensive documentation of TCR surface fluctuations.

The main features of surface thermodynamic fluctuations, as revealed by the composite analysis of all identified TCRs, include a persistent decrease in temperature, dewpoint temperature, and equivalent potential temperature from the outer to inner edge of the rainband. A clear undulation of pressure perturbations associated with the rainband was evident, with a minimum coincident with the outer edge and a maximum located inside the inner edge. The pressure fluctuations seen from the composite support the recent findings from a detailed case study of landfalling typhoon rainbands by YT, who documented similar wavelike variations of surface pressure associated with their studied rainbands. The composite kinematics of the TCRs was characterized by an obvious decrease in cross-band wind component, relatively minor variations in along-band wind component, and the wind veering. Peak winds and rainfall rates tended to occur inside the inner edge and they were roughly collocated, with a slight lag of the former.

Quantitative analyses indicate that the majority of the TCRs (~80%–90%) exhibited variations in surface temperature, pressure, wind speed, and wind direction of less than 2°C, 1.5 mb, 5 m s−1, and 20°, respectively. However, there was a fundamental dependence of the magnitude of TCR fluctuations on the radial distance from the tropical cyclone center, particularly possessing a clear trend of larger (smaller) thermodynamic fluctuations over outer (inner) regions of the cyclone.

Based on a radius threshold of 3 times the RMW, the TCRs identified in this study were further classified into the outer and inner rainbands. The composite and

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3 According to Houze (2010), most of the principal rainband lies within the inner-core region, except for a band segment near its upwind end that is probably located in the outer environment of a tropical cyclone.

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### Table 4. The mean values of frictionally induced vertical motions, vertical vorticity, and horizontal divergence calculated for the classified outer and inner rainbands.

<table>
<thead>
<tr>
<th></th>
<th>( \bar{W}_z ) (m s(^{-1}))</th>
<th>( \bar{\zeta} ) (s(^{-1}))</th>
<th>( \bar{D} ) (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer rainband</td>
<td>(-3.37 \times 10^{-3})</td>
<td>(-7.82 \times 10^{-6})</td>
<td>(-3.96 \times 10^{-5})</td>
</tr>
<tr>
<td>Inner rainband</td>
<td>(4.98 \times 10^{-2})</td>
<td>(5.11 \times 10^{-5})</td>
<td>(-1.82 \times 10^{-5})</td>
</tr>
</tbody>
</table>
magnitude analyses of their surface fluctuations indicate that the outer rainbands had a higher potential than the inner rainbands to reduce the near-surface $\theta_e$ values. This observed characteristic appears likely related to more pronounced evaporative cooling taking place in drier subcloud regions and the downward transport of low-$\theta_e$ air aloft by more vigorous convective downdrafts for the outer rainband. In addition, fundamentally different features of surface pressure fluctuations and mean frictional vertical velocity and relative vorticity between the outer and inner rainbands were also documented. These results reflect a possibly different origin. Nevertheless, there was no dramatic difference in the pattern of kinematic fluctuations between the outer and inner rainbands, and their mean magnitudes were also found to be statistically identical. These observational aspects did not suggest an entirely clear distinction of surface characteristics for these two types of rainbands. It is possible that the remote influences of the dynamics of the inner-core vortex still cannot be entirely ruled out as a potentially important factor in constraining the behavior of moist convection located over regions even far away from the cyclone center. Better clarification of this issue will rely largely on analyses of future detailed observations collected from a wide variety of TCRs located at different radial distances and encompassing both the inner core and outer regions of tropical cyclones.

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