Rapid Weakening of Tropical Cyclones in Monsoon Gyres over the Tropical Western North Pacific

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ABSTRACT

As one major source of forecasting errors in tropical cyclone intensity, rapid weakening of tropical cyclones [an intensity reduction of 20 kt (1 kt = 0.51 m s⁻¹) or more over a 24-h period] over the tropical open ocean can result from the interaction between tropical cyclones and monsoon gyres. This study aims to examine rapid weakening events occurring in monsoon gyres in the tropical western North Pacific (WNP) basin during May–October 2000–14.

Although less than one-third of rapid weakening events happened in the tropical WNP basin south of 25°N, more than 40% of them were associated with monsoon gyres. About 85% of rapid weakening events in monsoon gyres occurred in September and October. The rapid weakening events associated with monsoon gyres are usually observed near the center of monsoon gyres when tropical cyclone tracks make a sudden northward turn. The gyres can enlarge the outer size of tropical cyclones and tend to induce prolonged rapid weakening events with an average duration of 33.2 h. Large-scale environmental factors, including sea surface temperature changes, vertical wind shear, and midlevel environmental humidity, are not primary contributors to them, suggesting the possible effect of monsoon gyres on these rapid weakening events by modulating the tropical cyclone structure. This conclusion is conducive to improving operational forecasts of tropical cyclone intensity.

1. Introduction

Despite significant improvements in operational tropical cyclone track forecasts, there has been slower progress in intensity forecasting over the past two decades, especially during rapid intensity changes (e.g., Elsberry et al. 2007; DeMaria et al. 2014). Many studies have studied tropical cyclone rapid intensification (RI), which is a challenge in intensity forecasting (e.g., Kaplan and DeMaria 2003; Kaplan et al. 2010; Shu et al. 2012). In contrast, relatively little attention has been paid to tropical cyclone rapid weakening, an intensity decrease of 20 kt (1 kt = 0.51 m s⁻¹) or more in 24 h (DeMaria et al. 2012), particularly over tropical open waters (e.g., Brand 1973). The rapid weakening is one major source of large intensity forecasting errors as well (e.g., Wood and Ritchie 2015; Liang et al. 2016). Therefore, understanding of rapid weakening is important to the improvement of tropical cyclone intensity forecasting.

Our current understanding of tropical cyclone rapid weakening mainly comes from a few observational studies. The majority of them have shown that tropical cyclone rapid weakening can result from large-scale environmental factors. Zhang et al. (2007) suggested
the important role of dry air intrusion in the rapid weakening of Hurricane Lili (2002). Qian and Zhang (2013) found that the rapid weakening of Typhoon Babinca (2000) in the South China Sea was due to the rapid reduction in sea surface temperature (SST). Both DeMaria et al. (2012) and Wood and Ritchie (2015) examined rapid weakening events in the North Atlantic and eastern North Pacific tropical cyclones during the 1980s–2010s and showed that the strong SST gradient resulted in more rapid weakening events in the eastern North Pacific than in the Atlantic. The results of Wood and Ritchie (2015) also related these rapid weakening events to increasing vertical wind shear and dry air intrusion. Moreover, the internal process of tropical cyclones can lead to the rapid weakening, as suggested in Titley and Elsberry (2000). They attributed the rapid weakening of Typhoon Flo (1990) to a shallower secondary circulation caused by the downward extension of the upper-level eddy flux convergence of angular momentum.

Recently, Liang et al. (2016) noted the important effect of monsoon gyres in the tropical western North Pacific (WNP) basin on tropical cyclone rapid weakening. Through an observational analysis, they found that the rapid weakening of Typhoon Chan-Hom (2015) happened when it coalesced with a low-frequency (15–30 days) monsoon gyre. The interaction between these two systems induced the development of strong convection on the eastern side of the monsoon gyre, which prevented the inward transport of mass and moisture into Chan-Hom, leading to the collapse of the eastern part of the eyewall.

The monsoon gyre is a specific pattern of the low-level summertime monsoonal circulation on the intraseasonal time scale in the tropical WNP basin (e.g., Lander 1994; Carr and Elsberry 1995). Studies showed that the monsoon gyre can supply a favorable large-scale environment and initial disturbances for tropical cyclone formation (e.g., Ritchie and Holland 1999; Chen et al. 2004; Wu et al. 2013b; Liang et al. 2014), and that it can also lead to sudden track changes through interacting with tropical cyclones embedded in it (e.g., Carr and Elsberry 1995; Wu et al. 2011a,b, 2013a; Liang et al. 2011; Liang and Wu 2015; Bi et al. 2015). Based on Liang et al. (2016), such interactions with tropical cyclones, meanwhile, may affect the tropical cyclone intensity through changing tropical cyclone structure. Therefore, for advancing our understanding of tropical cyclone rapid weakening, a composite observational study is performed to characterize the rapid weakening in monsoon gyres in the tropical WNP basin (excluding the South China Sea) during May–October 2000–2014, by comparing with those rapid weakening events not occurring in monsoon gyres.

The rest of the paper is organized as follows. The data and methods for the identification of rapid weakening events in monsoon gyres are described in section 2. Statistical characteristics of rapid weakening events in and not in monsoon gyres and associated tropical cyclone activities are discussed in section 3. Section 4 compares the large-scale environmental characteristics corresponding to these two types of rapid weakening events. A brief summary is given in section 5.

2. Data and identification of rapid weakening in monsoon gyres

a. Data

The tropical cyclone information is taken from the Joint Typhoon Warning Center (JTWC) best track dataset, including tropical cyclone 6-hourly positions, intensities, and size parameters (radii of wind intensities of 34, 50 and 64 kt in each quadrant, excluding the year 2000). Monsoon gyres are identified from the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data, which are available at the surface and 26 pressure levels (from 1000 to 10 hPa) on 1° × 1° grids every 6 h (NOAA/NCEP 2000). Wu et al. (2013b) successfully identified monsoon gyres in this dataset. The National Oceanic and Atmospheric Administration (NOAA) daily outgoing longwave radiation (OLR) dataset on 2.5° × 2.5° grids is used to identify the deep convection associated with monsoon gyres (Liebmann and Smith 1996). We focus on the activities of tropical cyclones and monsoon gyres during May–October 2000–14 in this study.

The large-scale environmental data related to rapid weakening events are taken from the NOAA daily Optimum Interpolation Sea Surface Temperature, version 2 (OISSTv2), analysis (Reynolds et al. 2007) and the NCEP–DOE Reanalysis-2 wind and relative humidity products on pressure levels with spatial resolutions of 2.5°. The latter product provides 4-times-a-day and monthly values and less synoptic-scale influence during calculating the environmental parameters as a result of its coarse spatial resolution.

b. Identification of monsoon gyres

The identification method of monsoon gyres proposed by Wu et al. (2013b) is employed in this study. For reducing the residual of tropical cyclone information in filtering, tropical cyclone circulations were first removed from the unfiltered FNL wind fields based on Kurihara et al. (1993, 1995). Then low-pass filtered wind fields at 850 hPa were obtained by using the Lanczos filter (Duchon 1979) with a 10-day cutoff period. Candidate gyre centers were obtained according to relative circulation maxima in
850-hPa low-pass wind fields in the WNP basin, and the gyre size was visually determined as the diameter of the outermost closed wind vectors. Finally, we identified the cyclonic circulation with a diameter of at least 2500 km and a band of deep convection along its southern and southeastern periphery as a monsoon gyre. The details can be found in Wu et al. (2013b).

During May–October 2000–14, 43 monsoon gyres were identified in the WNP basin with an annual frequency of 2.9 monsoon gyres. Their lifespans range from 3 to 17 days with an average of 8.0 days. Figures 1a and 1b presents the locations of these monsoon gyres when they reached their relative circulation maxima, marked with blue dots, and their monthly number, respectively. Monsoon gyres usually occur south of 25°N with an active region bounded by 15°–25°N and 125°–143°E (outlined by a red rectangle in Fig. 1a). In agreement with Wu et al. (2013b), they are primarily observed in September and October (Fig. 1b).

c. Identification of rapid weakening in monsoon gyres

The tropical cyclone intensity decrease of 20 kt or more in 24 h is used to define rapid weakening events as suggested in DeMaria et al. (2012). They investigated the intensity changes of Atlantic tropical cyclones over the open ocean during 1982–2010 and found that the intensity decrease of 20 kt in 24 h roughly represented the 5th percentile. An examination of intensity changes of tropical cyclones over the tropical WNP from 1975 to 2014 showed a similar result.

Extratropical tropical cyclones were first removed from the tropical cyclone dataset and then tropical cyclone intensity changes at 24-h intervals were calculated. The criteria, including weakening in the first 6 h and no intensification in the following 18 h, were adopted to exclude intensity fluctuations caused by eyewall replacement (e.g., Kossin and Sitkowski 2012; Wood and Ritchie 2015). Previous numerical studies showed that the topographic effect on tropical cyclone intensity usually occurs in 6–9 h prior to landfall (e.g., Tuleya and Kurihara 1978; Huang and Liang 2010). To avoid intensity changes caused by the topographic effects, we further considered those tropical cyclones whose centers remained more than 200 km from the nearest landmass in 24 h. This yields a total of 272 24-h rapid weakening events in the WNP basin, corresponding to 80 tropical cyclones.

Brand (1973) suggested that weakening events of tropical cyclones at low latitudes (south of 25°N) over the open ocean are unusual and difficult to forecast because of the favorable environment for intensification. For more robustness, we calculated the ratio of the number of 6-h weakening events to the number of both 6-h intensification and weakening events on each grid to find the key region favorable for tropical cyclone weakening, named the weakening ratio. When the weakening ratio is larger than 0.5, more 6-h weakening events happen than 6-h intensification events, indicating the corresponding region is more favorable for tropical cyclone weakening. Figure 1a shows the weakening ratio overlapped with the average May—October SST during 1975–2014. A weakening ratio of higher than 0.9 along the coastline and over the landmass and islands agrees with the well-known negative effects of topography on tropical cyclone intensity.
(e.g., Brand and Blelloch 1973; Wu et al. 2003, 2009; Chou et al. 2011). In the WNP basin, both the spatial distributions of the weakening ratio and the average SST manifest an obvious boundary around 25°N. North of 25°N, the weakening ratio greater than 0.5 becomes larger with increasing latitude, and the average SST is lower than 28°C with a sharp SST gradient. This result agrees with previous studies that tropical cyclones usually undergo weakening when they move at mid- and high latitudes as a result of environments unfavorable for intensification (e.g., Hanley et al. 2001; Wood and Ritchie 2015). South of 25°N, Fig. 1a shows a high SST exceeding 28°C with a weak SST gradient, which is coupled with the weakening ratio lower than 0.5. Therefore, we regard the WNP basin south of 25°N as the region favorable for tropical cyclone intensification and focus on the 24-h rapid weakening events in this tropical basin. Note that no extratropical transition happened in these events. These restrictions produce a sample size of 79 24-h rapid weakening events for 33 tropical cyclones, revealing that only 29% of the 24-h rapid weakening events occurred in the tropical WNP basin.

Despite tropical cyclones not being prone to weakening in the tropical WNP basin based on the small weakening ratio, the weakening ratio in the active region (15°–25°N, 125°–143°E) of monsoon gyres is larger than that in the rest of the tropical WNP basin. As shown in Fig. 1c, which presents the deviation of the weakening ratio from its zonal average between 120° and 180°E, high positive deviations of the weakening ratio occur in the active region of monsoon gyres. It indicates that tropical cyclones in this region have a larger likelihood of weakening, which may be associated with the occurrence of monsoon gyres. Thus, the selection for rapid weakening events in monsoon gyres was performed by considering that the distance between the tropical cyclone center and the monsoon gyre center is less than the monsoon gyre size during a 24-h period. It shows that 33 24-h rapid weakening events for nine tropical cyclones were accompanied with monsoon gyres, which accounts for 42% (27%) of the total 24-h rapid weakening events (tropical cyclones) in the tropical WNP basin. The examination of yearly numbers of identified monsoon gyres and 24-h rapid weakening events shows that relatively more rapid weakening events happened in active years of monsoon gyres. Therefore, the monsoon gyre might be one of the important factors in the rapid weakening of tropical cyclones in the tropical WNP basin.

For verifying the identification method of rapid weakening in monsoon gyres, Figs. 2a and 2c show the storm-centered 16-km geostationary water vapor imagery and the unfiltered OLR overlapped with the 850-hPa 10-day low-pass wind field at the onset of an identified rapid weakening event in monsoon gyres. The black rectangle in Figs. 2a and 2b outlines the region displayed in Figs. 2c and 2d. The water vapor imagery is helpful in determining the location of deep convection, where the blue area indicates the cold cloud top with a temperature lower than −50°C. It shows that the tropical cyclone is embedded in a low-frequency cyclonic circulation with a diameter of about 3000 km near 20°N, 140°E. A band of deep convection is observed along its southeastern periphery, which is determined based on the band area with the cloud top of −50°C (blue) in Fig. 2a and the OLR lower than 200 W m⁻² in Fig. 2c. In an identified case of rapid weakening not in monsoon gyres (Figs. 2b and 2d), the tropical cyclone is trapped in a monsoon trough with the bottom extending to the east of 160°E. Thus, the identification method in this study can capture well the rapid weakening events in monsoon gyres.

Moreover, it is noteworthy that on average a tropical cyclone in a monsoon gyre would experience more than three 24-h rapid weakening events, compared to fewer than two 24-h rapid weakening events with the absence of monsoon gyres. Thus, more 24-h rapid weakening events would happen in the tropical cyclone lifetime with the interaction between monsoon gyres and tropical cyclones.

3. Characteristics of rapid weakening in monsoon gyres

a. Statistical features

The statistical features of 24-h rapid weakening events in monsoon gyres in the tropical WNP basin are first examined. Figure 3a shows the monthly number of 24-h rapid weakening events. The peak of 24-h rapid weakening events occurs in October regardless of the occurrence of monsoon gyres. Compared to those weakening events not in monsoon gyres with a relatively similar number of occurrences in each month, up to 85% of 24-h rapid weakening events in monsoon gyres are observed in September and October, corresponding to the peak occurrence of monsoon gyres in Fig. 1b.

Figure 3b presents the normalized frequency of 24-h rapid weakening events by intensity at onset based on the total number of tropical cyclones. Almost all 24-h rapid weakening events happen when tropical cyclones reach typhoon intensity or stronger. The probability of rapid weakening in monsoon gyres increases with increasing tropical cyclone intensity, while tropical cyclones with an intensity between 130 and 139 kt are the most likely to undergo the rapid weakening with no involvement of monsoon gyres. Note that there are still a few 24-h rapid weakening events not in monsoon gyres.
with tropical storm intensity, which may result in a stronger average intensity of tropical cyclones in monsoon gyres. It is found that the average peak intensity of tropical cyclones in monsoon gyres exceeds 140 kt, which is about 20 kt stronger than that of tropical cyclones not in monsoon gyres.

In addition, nearly 70% of tropical cyclones undergo the intensity decrease of 20–25 kt in 24 h regardless of the occurrence of monsoon gyres (Fig. 3c). But some tropical cyclones embedded in monsoon gyres still experience great reductions exceeding 40 kt in 24 h.

The number of 24-h rapid weakening events and corresponding tropical cyclones suggest that some 24-h rapid weakening events may be persistent. For example, if two 24-h rapid weakening events start at \( t \) hours and \( t + 6 \) h, respectively, we regard them as consecutive 24-h rapid weakening events, which will be combined into a persistent rapid weakening event with a duration of 30 h. Thus, for removing the repeated effects caused by consecutive 24-h rapid weakening events during the following composite analysis, we ignore consecutive 24-h rapid weakening events and obtain a total of 13 (28) persistent rapid weakening events in (not in) monsoon gyres with the average duration of 33.2 (27.4) h. The number of corresponding tropical cyclones does not decrease. Further examination of the duration of persistent rapid weakening events in Fig. 3d shows that up to 77% of total persistent rapid weakening events in monsoon gyres have at least two consecutive 24-h rapid weakening events with the longest duration of 54 h, while more than 60% of those events not in monsoon gyres can only last 24 h. Figure 3d suggests that monsoon gyres can lead to a prolonged rapid weakening of tropical cyclones embedded in them. The following composites will be obtained by using persistent rapid weakening events.

b. Associated tropical cyclone activity

Based on Liang et al. (2016), the rapid weakening of Typhoon Chan-Hom (2015) was accompanied with the coalescence of the typhoon with a monsoon gyre and a sudden northward turn. Therefore, the positions of persistent rapid weakening events in monsoon gyres and the tracks of corresponding tropical cyclones were first
investigated. Figures 4a and 4b illustrate the composite 200- and 850-hPa 10-day low-pass filtered wind fields at the onset time of persistent rapid weakening and the locations of tropical cyclones with respect to monsoon gyre centers. In the lower troposphere (850 hPa; Fig. 4b), there is a nearly circular gyre with a diameter of about 3000 km and enhanced southwesterly flows along the southeastern periphery. A weak anticyclonic vortex to its southeast is associated with the Rossby wave energy dispersion of the monsoon gyre (Carr and Elsberry 1995; Liang et al. 2011, 2016; Wu et al. 2011a,b, 2013b). The majority of persistent rapid weakening events happen near the center of the composite monsoon gyre. The composite 200-hPa 10-day low-pass filtered wind field (Fig. 4a) shows an anticyclonic circulation about 750 km northeast of the center of composite monsoon gyres with a westerly jet to the north. The large-scale wind fields in the lower and upper troposphere are consistent with the structure of the composite monsoon gyre in Wu et al. (2013b), which would induce a relative low vertical wind shear in the vicinity of the monsoon gyre center according to Wu et al. (2013b). Figure 4c displays the tracks of tropical cyclones experiencing rapid weakening in monsoon gyres. The persistent rapid weakening events in monsoon gyres happen prior to and during the northward turns of tropical cyclones. A further examination shows that monsoon gyres usually move with tropical cyclones during the northward turn, in agreement with previous studies (e.g., Liang et al. 2011, 2016; Wu et al. 2011a,b, 2013b). Therefore, Fig. 4 suggests that the rapid weakening usually happens when tropical cyclones coalesce with monsoon gyres and that it undergoes a sudden northward turn, confirming the case study in Liang et al. (2016).

For further comparison, Fig. 5 shows the composite 850- and 200-hPa 10-day low-pass filtered wind fields and the tracks of tropical cyclones with persistent rapid weakening events not in monsoon gyres. Persistent rapid weakening events not in monsoon gyres are mainly located on the bottom of the composite monsoon trough with prevailing intense southwest-southerly flows at 850 hPa and weak northerly flows to the east of the South Asian anticyclone at 200 hPa (Figs. 5a and 5b). The high vertical wind shear may be responsible for these persistent rapid weakening events, which will be examined in section 4. The majority of tropical cyclones not in monsoon gyres move northward along the western periphery of the WNP subtropical high and to the south of the weak upper-tropospheric westerly trough when they experience rapid weakening events, as shown in Fig. 5c. Shu et al. (2012) found that the dry air associated with the WNP subtropical high can intrude into the southwestern part of the inner core of tropical cyclones moving along the western periphery of the WNP.
subtropical high, leading to the weakening of tropical cyclones. Thus, the effect of environmental humidity on rapid weakening will be examined in section 4.

Additionally, we note that persistent rapid weakening events over the tropical open ocean usually occur in the early and middle lifespan of tropical cyclones (Figs. 4c and 5c). On average, tropical cyclones in (not in) monsoon gyres can maintain 100 (112.5) h after their first continuous rapid weakening. Thus, the following intensity evolution of tropical cyclones after their first rapid weakening was examined.

Figure 6 shows the intensity evolutions of tropical cyclones with rapid weakening events in and not in monsoon gyres from −24 h to the end of the average

FIG. 4. Composite (a) 200- and (b) 850-hPa 10-day low-pass filtered wind fields (vector and contour, m s\(^{-1}\)) and locations (red dots) of tropical cyclone centers with respect to the center of the monsoon gyre (blue dot) at the onset time of persistent rapid weakening events. (c) Tracks of tropical cyclones experiencing the rapid weakening in monsoon gyres. Red lines and dots highlight periods of rapid weakening.

FIG. 5. Composite (a) 200- and (b) 850-hPa 10-day low-pass filtered wind fields (shaded and contour, m s\(^{-1}\)) and locations (red dots) of persistent rapid weakening events not in monsoon gyres at onset. (c) Tracks of tropical cyclones experiencing the rapid weakening not in monsoon gyres. Red lines highlight periods of rapid weakening.
duration with composite intensity evolutions indicated by black lines. In this study, we use the ratio of tropical cyclone intensity to the intensity of the first persistent rapid weakening event at onset to investigate the effect of rapid weakening on the following intensity change. In the figure, 0 h indicates the first onset time of the rapid weakening event in the tropical cyclone life.

As a crucial parameter for determining tropical cyclone impacts, the effect of monsoon gyres on tropical cyclone size was also examined. In this study, the average radii of surface wind intensities of 34, 50, and 64 kt are used to quantify the size of the entire tropical cyclone, the extent of wind damages, and the hurricane-force wind, respectively (e.g., Merrill 1984; Weatherford and Gray 1988; Kimball and Mulekar 2004; Wu et al. 2015). Because of the unavailability of tropical cyclone size parameters in the year 2000, 12 (26) persistent rapid weakening events in (not in) monsoon gyres for 8 (24) tropical cyclones are used to obtain composite tropical cyclone sizes. Figure 7 presents the evolution of composite tropical cyclone sizes from −24 to 24 h with 0 h denoting the onset time of the first rapid weakening. Tropical cyclones embedded in monsoon gyres have larger 34- and 50-kt wind radii. During rapid weakening, all three size parameters show almost consistent increasing rates regardless of the interaction with monsoon gyres. Previous studies suggested a negative correlation of the 34-kt radius with the tropical cyclone intensity change (e.g., Kimball and Mulekar 2004; Carrasco et al. 2014). Thus, the monsoon gyres can enlarge the entire size and the damage extent of tropical cyclones in them, which might be a factor in why they weaken more than tropical cyclones not in monsoon gyres.

4. Environmental factors associated with rapid weakening in monsoon gyres

The effects of environmental factors on the weakening of tropical cyclones are well known (e.g., Zhang et al. 2007; DeMaria et al. 2012; Qian and Zhang 2013; Wood and Ritchie 2015). Tropical cyclones may undergo rapid weakening when they move over a region with low SST and a strong SST gradient, and undergo dry air intrusion and high vertical wind shear. However, Liang et al. (2016) found that the rapid weakening of Chan-Hom (2015) over
the tropical open ocean was related to its interaction with a low-frequency monsoon gyre. Therefore, the large-scale environmental characteristics with rapid weakening events in monsoon gyres were examined by comparing them to those events not in monsoon gyres.

a. SST changes

Figures 8a and 8b depict composite SST fields from the NOAA OISSTv2 analysis during persistent rapid weakening events in and not in monsoon gyres. All persistent rapid weakening events begin when tropical cyclones move over the ocean with SST exceeding 27°C, which is higher than the threshold for tropical cyclone development (e.g., Chan et al. 2001). However, the rapid weakening may happen when tropical cyclones move over regions with decreasing SST even though the local SST is high (e.g., Wood and Ritchie 2015). Thus, the SST changes relative to the SST 1 day before the rapid weakening events are investigated in Fig. 8c, which presents composite SST differences averaged within a radius of 500 km from tropical cyclone centers during persistent rapid weakening events. We can see a slight decrease, with the value smaller than 0.1°C during the rapid weakening regardless of the occurrence of monsoon gyres. Thus, the SST change is not a potential contributor to rapid weakening events in the tropical WNP basin regardless of the occurrence of monsoon gyres.

Moreover, the negative oceanic feedback induced by tropical cyclone passage has important impacts on tropical cyclone intensity changes (e.g., Chang and Anthes 1978; Price 1981; Schade and Emanuel 1999; Bender and Ginis 2000). Previous studies suggested that slower-moving tropical cyclones can strengthen the negative oceanic feedback by enhancing tropical-cyclone-induced SST cooling, thus limiting tropical cyclone intensity (Wang and Wu 2004; Lin et al. 2009; Zedler 2009; Mei et al. 2012). Figure 9 shows composite translation speeds of tropical cyclones in and not in monsoon gyres from −24 to 24 h with 0 h indicating the onset of persistent rapid weakening events. The translation speed is measured by dividing the sum of the distance between tropical cyclone positions 6 h prior to and after reaching this position by 12 h. It shows that tropical cyclones not in monsoon gyres move with a
composite translation speed around 5.0 m s\(^{-1}\) prior to and during the rapid weakening, in agreement with the average translation speed of 4.5–5.6 m s\(^{-1}\) when the tropical cyclone intensity reaches tropical storm as suggested in Mei et al. (2012). In monsoon gyres, the translation speed is 0.5–1.0 m s\(^{-1}\) slower, which may be associated with the slower westward component before sudden northward turns (e.g., Carr and Elsberry 1995; Wu et al. 2011a,b, 2013a; Liang et al. 2011; Liang and Wu 2015). Thus, tropical cyclones with rapid weakening in this study cannot be regarded as slower-moving cases, which may cause small amplitudes of tropical-cyclone-induced SST cooling based on Mei et al. (2012). Further examination of the SST cooling was conducted. The SST anomaly was first calculated as the difference between the SST during rapid weakening and 1 day prior to the generation of tropical cyclones. Then the SST cooling was defined as the maximum negative SST anomaly averaged within a region with a radius of 200 km from tropical cyclone centers during the rapid weakening. On average, the SST decreases by 0.71°C (0.25°C) during the passage of tropical cyclones in (not in) monsoon gyres. The higher SST cooling for tropical cyclones in monsoon gyres suggests that the SST cooling effect might be a contributor to the difference between rapid weakening events in and not in monsoon gyres. However, Mei et al. (2012) found that tropical cyclones would weaken, with the tropical-cyclone-induced SST cooling exceeding 2.5°C. Therefore, the tropical-cyclone-induced SST cooling does not have predominant impacts on the occurrence of rapid weakening events.

b. Midlevel environmental humidity

The midlevel environmental humidity, which is usually measured by the average relative humidity between 700 and 500 hPa, has an important effect on tropical cyclone intensity changes. Shu and Wu (2009) found that the midlevel dry air intrusion into the inner core and the region within the radius of 360 km from the tropical cyclone center would lead to the weakening of tropical cyclones. Wood and Ritchie (2015) also showed that rapid weakening events in the tropical eastern North Pacific and North Atlantic were likely related to the midlevel dry air intrusion and the decrease of midlevel moisture, respectively. Figure 10 shows the differences
between composite midlevel relative humidity fields averaged from $-24$ to $0$ h and from $0$ h to the end of the persistent rapid weakening events. For rapid weakening events in monsoon gyres (Fig. 10a), the composite relative humidity within the radius of 360 km increases on the eastern side of a tropical cyclone during rapid weakening, indicating that there is no dry air intrusion. But an evident dry air intrusion in the southwest quadrant is observed for those events not in monsoon gyres, as shown in Fig. 10b. The composite relative humidity decreases by 10% around the radius of 360 km on the southwestern side of a tropical cyclone during rapid weakening. Thus, the large-scale midlevel humidity change is not a primary factor in the rapid weakening of tropical cyclones interacting with monsoon gyres.

c. Vertical wind shear

Vertical wind shear is also a major impacting factor in tropical cyclone intensity changes, which has been highlighted by many studies (e.g., DeMaria 1996; Frank and Ritchie 2001; Wong and Chan 2004). The 200–850-hPa vertical wind shear higher than 9 m s$^{-1}$ and the low-level vertical wind shear higher than 2.5 m s$^{-1}$ are usually unfavorable for tropical cyclone intensification. Both Shu et al. (2013) and Wang et al. (2015) suggested that the low-level vertical wind shear can better reflect the effect on intensity changes of tropical cyclones in the active season in the WNP basin. Therefore, Fig. 11 compares composite 200–850-hPa and low-level vertical wind shears between rapid weakening events in and not in monsoon gyres from $-24$ to $24$ h. For reducing biases caused by tropical cyclone structure, tropical cyclone circulations were first removed from horizontal wind fields at 200 and 850 hPa based on Kurihara et al. (1993, 1995). Then the vertical wind shears averaged over a region within the radius of 500 km from the tropical cyclone center were measured by the differences of the horizontal winds between 200 and 850 hPa (200 − 850 hPa) and between 850 and 1000 hPa (low level), respectively. In spite of the slight increases in both vertical wind shears prior to and during the rapid weakening in monsoon gyres, the composite 200–850 hPa and low-level vertical wind shears remain with values lower than 8 and 2.5 m s$^{-1}$, respectively. The low vertical wind shear may be related to weak horizontal winds near the monsoon gyre center in the lower and upper troposphere in Figs. 4a and 4b, which agrees with the result of Wu et al. (2013b). For those events not in monsoon gyres, high vertical wind shears exceed thresholds during the rapid weakening, which may result from weak northerly winds in the upper troposphere and strong southerly winds in lower troposphere, as shown in Figs. 4a and 4b. Figure 11 indicates that vertical wind shear is not a crucial factor in rapid weakening events in monsoon gyres.

The analysis of the main environmental factors confirms that the rapid weakening of tropical cyclones in monsoon gyres in the tropical WNP basin usually happens in an environment favorable for tropical cyclone intensification, the mechanism for which may be quite different from rapid weakening events investigated by previous studies (e.g., Titley and Elsberry 2000; Zhang et al. 2007; DeMaria et al. 2012; Qian and Zhang 2013; Wood and Ritchie 2015). Based on the observational results of Liang et al. (2016), the possible important effect of monsoon gyres should be taken into account and warrants further exploration.

5. Summary

The possible influence of monsoon gyres on the intensity change of tropical cyclones has not been well understood compared to their effects on tropical cyclone formation and track changes in the WNP basin (e.g., Carr and Elsberry 1995; Ritchie and Holland 1999; Chen...
et al. 2004; Wu et al. 2011a,b, 2013a,b; Liang et al. 2011, 2014; Liang and Wu 2015). Thus, a composite observational study was conducted on the characteristics of rapid weakening events in monsoon gyres in the tropical WNP basin south of 25°N during May–October 2000–14.

Our analysis shows that only 29% of rapid weakening events happened in the tropical WNP basin south of 25°N. However, up to 42% of them, including 33 24-h rapid weakening events for nine tropical cyclones, were associated with the activity of monsoon gyres. About 85% of the 24-h rapid weakening events in the monsoon gyres occurred in September and October, which corresponds to the peak season of monsoon gyres. The interaction between monsoon gyres and tropical cyclones would lead to a prolonged rapid weakening period with the longest duration of 54 h and an average duration of 33.2 h.

The analysis of the main environmental factors suggests that the rapid weakening in monsoon gyres is not primarily caused by the changes of large-scale factors, in agreement with the case study of Liang et al. (2016). Note that the SST cooling during the passage of tropical cyclones might be a contributor to the difference between rapid weakening events in and not in monsoon gyres. These unusual events usually happen near the center of monsoon gyres and are accompanied with a northward turn of tropical cyclones. Monsoon gyres enlarge the outer size of the tropical cyclones embedded in them, which might be a factor in greater intensity reductions of tropical cyclones in monsoon gyres. The intensity of tropical cyclones with rapid weakening in monsoon gyres usually manifests a sharper decreasing rate after the rapid weakening compared to those not in monsoon gyres, which suggests that the prolonged rapid weakening of tropical cyclones caused by monsoon gyres may further limit their following intensification. Therefore, based on the possible mechanism proposed by Liang et al. (2016) that monsoon gyres can lead to the rapid weakening of tropical cyclones by modulating tropical cyclone structure, the possible important effect of monsoon gyres on these rapid weakening events should be further investigated, which may be conducive to improving the capability of forecasting the rapid weakening of tropical cyclones over the tropical open ocean.

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REFERENCES


Brand, S., 1973: Tropical cyclone structure, the possible important effect of monsoon gyres usually manifests a sharper decreasing rate after the rapid weakening compared to those not in monsoon gyres, which suggests that the prolonged rapid weakening of tropical cyclones caused by monsoon gyres may further limit their following intensification. Therefore, based on the possible mechanism proposed by Liang et al. (2016) that monsoon gyres can lead to the rapid weakening of tropical cyclones by modulating tropical cyclone structure, the possible important effect of monsoon gyres on these rapid weakening events should be further investigated, which may be conducive to improving the capability of forecasting the rapid weakening of tropical cyclones over the tropical open ocean.

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REFERENCES


——, Y. Rao, Z. Tan, and D. Schönenmann, 2015: A statistical analysis of the effects of vertical wind shear on tropical cyclone intensity


