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Re-examination of Tropical Cyclone Formation in Monsoon Troughs over the Western North Pacific

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ABSTRACT

The monsoon trough (MT) is one of the large-scale patterns favorable for tropical cyclone (TC) formation over the western North Pacific (WNP). This study re-examines TC formation by treating the MT as a large-scale background for TC activity during May–October. Over an 11-year (2000–10) period, 8.3 TC formation events on average per year are identified to occur within MTs, accounting for 43.1% of the total TC formation events in the WNP basin. This percentage is much lower than those reported in previous studies. Further analysis indicates that TC formation events in monsoon gyres were included at least in some previous studies. The MT includes a monsoon confluence zone where westerlies meet easterlies and a monsoon shear line where the trade easterlies lie north of the monsoon westerlies. In this study, the large-scale flow pattern associated with TC formation in the MT is composited based on the reference point in the confluence zone where both the zonal and meridional wind components are zero with positive vorticity. While previous studies have found that many TCs form in the confluence zone, the composite analysis indicates that nearly all of the TCs formed in the shear region, since the shear region is associated with stronger low-level relative vorticity than the confluence zone. The prevailing easterly vertical shear of zonal wind and barotropic instability may also be conducive to TC formation in the shear region, through the development of synoptic-scale tropical disturbances in the MT that are necessary for TC formation.

Key words: monsoon trough, tropical cyclone formation, summer monsoon, vertical wind shear

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1. Introduction

The summertime monsoon trough (MT) over the western North Pacific (WNP) is a convergence zone in the lower troposphere, where westerly monsoon winds are found in its equatorward region, while easterly trade winds exist poleward of the trough. A number of studies have shown that the MT is an important large-scale circulation pattern associated with tropical cyclone (TC) formation in the WNP basin [e.g., Gray, 1968; Ramage, 1974; Holland, 1995; Lander, 1996; Briegel and Frank, 1997; Ritchie and Holland, 1999; see Li (2012) for a review]. The MT can provide both dynamical and thermodynamical large-scale conditions that are favorable for TC formation, including strong low-level cyclonic relative vorticity, high mid-level relative humidity, and weak vertical wind shear (Sadler, 1967; Gray, 1968; Ramage, 1974; Gray, 1975; Frank, 1987; Chia and Ropelewski, 2002; Harr and Chan, 2005; Chen et al., 2006). Although many studies have documented the percentages of TCs that form in the MT (e.g., Frank, 1987; McBride, 1995; Briegel and Frank, 1997; Ritchie and Holland, 1999), Molinari and Vollaro (2013) noticed that the results of these observational studies were examined mainly in a subjective manner, even without a common definition of the MT. As mentioned in Molinari and Vollaro (2013), for example, the MT was subjectively defined in Briegel and Frank (1997) and Ritchie and Holland (1999) and details about how a TC was considered to be associated with the MT were not mentioned.

As an alternative, Wu et al. (2012) and Molinari and Vollaro (2013) recently defined the MT as a geographical region in terms of monthly mean 850 hPa relative vorticity. Wu et al. (2012) used the mean relative vorticity averaged over 5°–20°N to define the zonal variation of the MT intensity, and it was not allowed to exist beyond the specified latitude range. In Molinari and Vollaro (2013), the MT was defined for each month as the contiguous region with positive monthly mean 850 hPa relative vorticity. Considering significant movement and structural changes of the MT on multiple time scales (Harr and Wu, 2011), uncertainty still exists in Wu et al. (2012) and Molinari and Vollaro (2013). That is, some formation events that were not associated with the MT may have

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been counted, while some formation events that formed beyond the specified latitude ranges may have been missed. In addition, the positive relative vorticity of the MT in their definition also includes the contribution from other systems, such as monsoon gyres. In other words, TCs that form in monsoon gyres were included in Wu et al. (2012) and Molinari and Vollaro (2013). Wu et al. (2013) showed that 19.8% of all May–October TCs over the WNP formed in monsoon gyres over the period 2000–10.

Although the MT is a large-scale summertime flow pattern over the WNP, it includes TCs and wave trains on the synoptic timescale that can alter convection, wind, and vorticity, which leads to changes in the structure and position of the MT (Holland, 1995; Lander, 1996; Harr and Wu, 2011). For example, northwestward-propagating wave trains have a typical wavelength of 2500–3000 km and a timescale of 6–10 days, consisting of alternating regions of cyclonic and anticyclonic circulation (Lau and Lau, 1990; Chang et al., 1996; Sobel and Bretherton, 1999; Li et al., 2003, 2006; Li and Fu, 2006; Fu et al., 2007; Chen and Huang, 2009). Numerical studies suggest that the presence of the MT is important for the generation of synoptic wave trains, and thus TC formation (Kuo et al., 2001; Aiyyer and Molinari, 2003; Li, 2006; Gall et al., 2010; Gall and Frank, 2010). In addition to providing large-scale conditions favorable for TC formation, these studies suggest that the synoptic-scale wave trains play an important role in how the MT affects TC formation in the WNP basin.

In order to investigate how the MT affects the development of synoptic-scale wave trains and subsequent TC formation, this study proposes a new approach for identifying the MT and the associated TC formation events. That is, the MT is treated as the background for the activity of synoptic systems including wave trains and TCs. Unlike previous studies in which large-scale patterns were composited with respect to TC centers, the dynamic composite in this study is conducted with respect to the reference point or the easternmost end of the MT. The reference point here refers to the point in the confluence zone where both the zonal and meridional wind components are zero with positive vorticity. It is conceivable that the identified TC formation events and the associated structure of the MT should be more reasonable due to a lack of contamination of the synoptic-scale circulation. The TC formation events associated with the MT in May–October during the period 2000–10 are examined in this study.

2. Data and methodology

2.1. *Data*

Three datasets are used in this study: (1) National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data with $1^\circ \times 1^\circ$ grids at six hour intervals (http://rda.ucar.edu/datasets/ds083.2/); (2) European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data with $1.5^\circ \times 1.5^\circ$ grids (Simmons et al., 2007); and (3) Joint Typhoon Warning Center (JTWC) best track data. In this study, the FNL wind fields are utilized in identifying the MT and compositing the MT structure. The 850 hPa monthly winds from ERA-interim data are also used to compare the identified TC formation events with those in Molinari and Vollaro (2013). TC formation is defined when the maximum sustained wind of a TC first exceeds 34 knots in the JTWC best track data.

2.2. *Identification of monsoon troughs and the associated TC formation*

In the American Meteorological Society (AMS) Glossary of Meteorology (http://amsglossary.allenpress.com/glossary), an MT is defined as a line of the minimum sea level pressure in monsoonal regions. However, most previous studies treated a MT as a circulation pattern in the lower troposphere with convergence/confluence between westerly monsoon winds and easterly trade winds (e.g., Frank, 1982; Lander, 1996; Briegel and Frank, 1997; Ritchie and Holland, 1999). Ritchie and Holland (1999) further categorized a MT as a monsoon confluence zone where westerlies meet easterlies and a monsoon shear line where the trade easterlies lie north of the monsoon westerlies.

Following these studies, the 850 hPa low-pass filtered winds and the associated relative vorticity are used to identify MTs. As we know, it is not unusual that multiple TCs are observed simultaneously in the WNP basin. Hsu et al. (2008) revealed that extreme events such as TCs contribute significantly to the seasonal mean and the intraseasonal and interannual variance of the 850 hPa vorticity along the TC tracks in the tropical WNP because the time averaging and filtering processes are unable to remove higher-frequency signals. Following Hsu et al. (2008) and Wu et al. (2013), the TC circulation in the FNL data is first removed with the procedure proposed by Kurihara et al. (1993, 1995).

After removal of the TC circulation, a 10-day low-pass Lanczos filter is applied to the wind field to obtain the low-frequency background wind field (Duchon, 1979). Figure 1 shows an example of the MT with the 850 hPa low-pass filtered wind field. At 0000 UTC 7 July 2006 (Fig. 1a), the MT can be roughly identified with the equatorial westerly flows that extend all the way to about 160°E and easterly trade winds on the poleward side. Typhoon Ewiniar (2006) and a distinct cyclonic circulation to the southeast of Ewiniar can be seen in the trough. About two and a half days later (Fig. 1b), the cyclonic circulation of Typhoon Bilis (2006) becomes dominant in the wind field and it is hard to visually identify the trough. In the corresponding 10-day low-pass filtered wind fields (Figs. 1c and d), however, the MT is well defined. Figures 1e and f are the synoptic-scale wave trains that distort the MT in Figs. 1a and b. Here, the synoptic-scale flow is defined as the difference between the unfiltered winds and the low-pass filtered winds. Figure 1 suggests that the low-pass filtering can effectively separate the large-scale MT from the synoptic-scale systems, such as TCs and wave trains, consistent with results from Fu et al. (2007, 2012) and Xu et al. (2013).

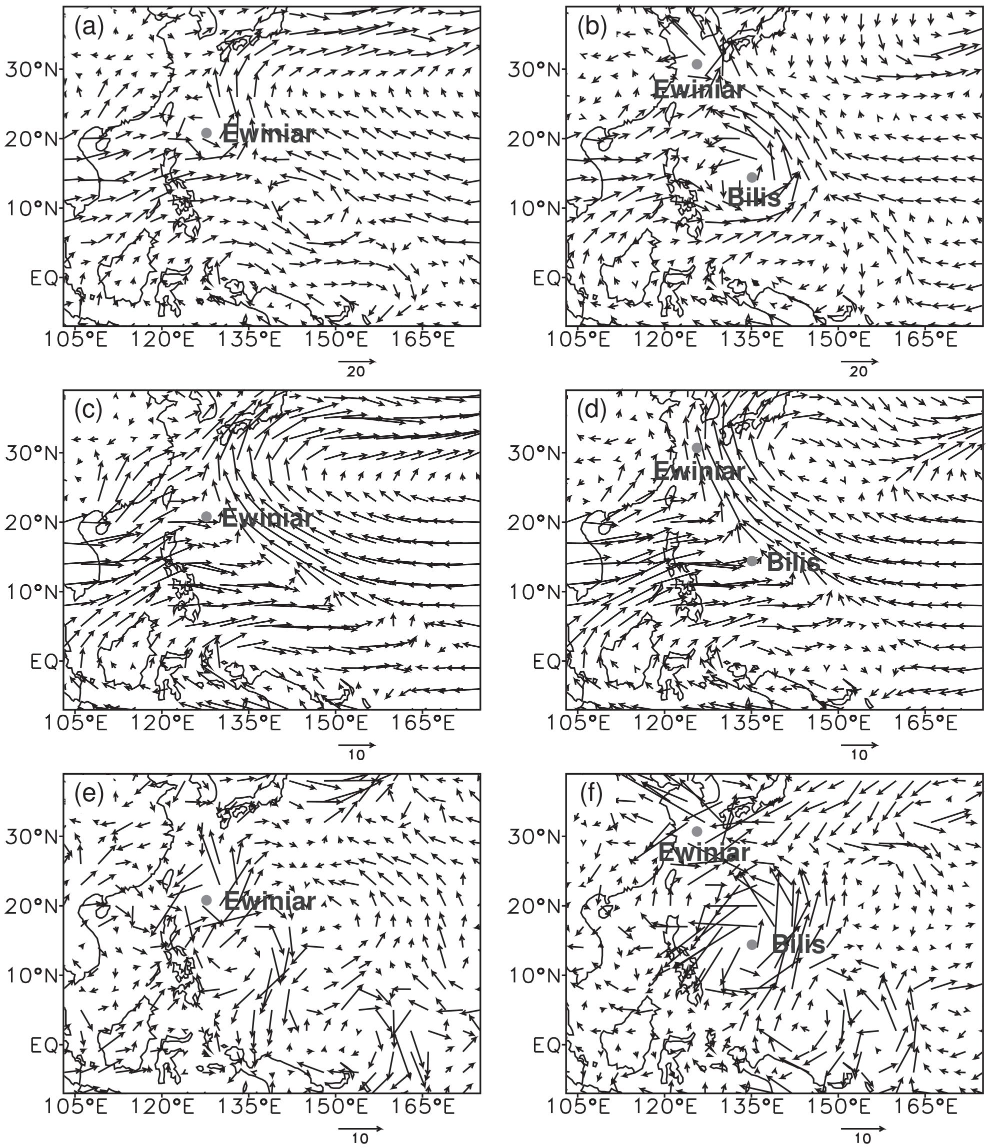

Fig. 1. (a, b) 850 hPa unfiltered winds, (c, d) 10-day low-pass filtered winds (m s^{-1}), and (e, f) 10-day high-pass filtered winds (m s^{-1}) at (a, c, and e) 0000 UTC 7 July 2006 and (b, d, and f) 1200 UTC 9 July 2006, with the dots indicating the centers of Typhoon Ewiniar (2006) and Bilis (2006).

The MT mainly prevails in the WNP basin from early or middle May to late September (e.g., Murakami and Matsumoto, 1994; Lau and Yang, 1997; Wu and Zhang, 1998; Hsu et al., 1999; Zhang et al., 2002). In this study, we focus on the MT activity and the associated TC formation (0°–30°N, 105°E–180°) in May–October during the period 2000–10. 80.8% of TCs (211 out of 261) were observed during the period. Following Ritchie and Holland (1999), an MT in this study includes two parts. The first part consists of westerly monsoon flows on the equatorward side and easterly trade flows on the poleward, which is called a monsoon shear line or an MT shear region. The second part is a confluence zone to the easternmost end of the shear line, where westerly monsoon flows from the west meet easterly trade flows from the east. First, to identify the changes of the zonal winds, the MT axis is determined with the line of the zero-zonal wind and positive relative vorticity at 850 hPa. The successive westerly winds (easterly winds) to the west (east) of the MT axis and positive relative vorticity at 850 hPa are then examined to determine the western (eastern) part of the MT. Considering that the easterlies to the east of the MT axis can extend to the eastern Pacific, the negative zonal stretching deformation in the predetermined area is also checked to determine the eastern boundary of the MT. Generally, the MT region extends up to 1500 km from its axis. Once the MT is determined, if a TC forms within this area, it is identified as a TC formation event within the MT.

We should mention that the low-pass Lanczos filter cannot completely remove the synoptic timescale component, especially in the vicinity of the cut-off period (10 days). As a result, the low-pass filtered winds are capable of capturing the migration of MTs on the timescale of several days. Figure 2 shows an example of the migration of a MT in the zonal and meridional directions. Note that the MT axis was identified with the line of the zero contour of the low-frequency 850 hPa zonal wind in the monsoon trough. At 0600 UTC 23 June 2006, the MT extended from Indonesia to 140°E to the south of the Philippines. A week later (30 June 2006), the trough migrated northeast by about 10° of latitude, extending from Hainan Island to 150°E. At 0600 UTC 7 July 2006, the trough moved further northeast and the east end reached 170°E. As shown in Fig. 2, the MT subsequently retreated southwest. The migration was accompanied by an orientation change of the MT, as well as the MT shape, which can be seen in the low-pass filtered 850 hPa wind fields (figure not shown). Such a low-frequency variation of the MT is closely related to the atmospheric intraseasonal oscillation (ISO) (Li and Wang, 2005; Li, 2010; Hsu and Li, 2011), and also the quasi-biweekly oscillation (QBWO) in the region (Kikuchi and Wang, 2009). Some studies have shown that TC formation can be influenced by the ISO and QBWO modes through their modulations of the MT (e.g., Ko and Hsu, 2009; Li and Zhou, 2013).

2.3. *Dynamic composite analysis*

We noticed that the composite analyses in previous studies were based mainly on TC or tropical depression (TD) centers (Briegel and Frank, 1997; Ritchie and Holland, 1999; Fu et al., 2007; Xu et al., 2013). Given the large variation in the relative positions of TC formation within MTs, the composited large-scale patterns may be a poor representation of the large-scale background for TC formation. In this study, the composite is conducted based on a reference point. The reference point is in the confluence zone where both the zonal and meridional wind components are zero with positive vorticity. The longitude of the reference point can be used to indicate the eastward extension/westward retreat of the MT.

Two typical types of MTs are identified in our analysis. Seventy-three TC formation events are found within southeast–northwest (SE–NW) oriented MTs, while 18 TC formation events occurred in west–east (W–E) oriented troughs. The SE–NW oriented MTs are dominant during summer in the WNP, as shown in Figs. 1c and d. This type of MT is very similar to the one in the monthly mean 850 hPa wind field. The other type of MT is largely zonally oriented, whose axes are nearly parallel to the equator. Lander (1996) showed that there are reverse-oriented MTs with their western ends in the tropics extending northeastward into subtropical latitudes. Such reverse-oriented MTs are excluded in this study.

Although the SE–NW oriented MTs in our study are predominant, accounting for 80.2%, the orientation of these MTs varies significantly. To reduce the uncertainty in our composite analysis, the MT orientation is rotated to the mean orientation based on 91 troughs around the reference point. First, as mentioned before, the MT axis is identified by the connecting line of the zero-zonal wind in the monsoon trough. Second, a straight line is used to fit the MT axis, and the angle between the axis and the equator is calculated. Finally, the MT axis is rotated to the mean angle and all of the variables in the following discussion are also adjusted based on the rotation.

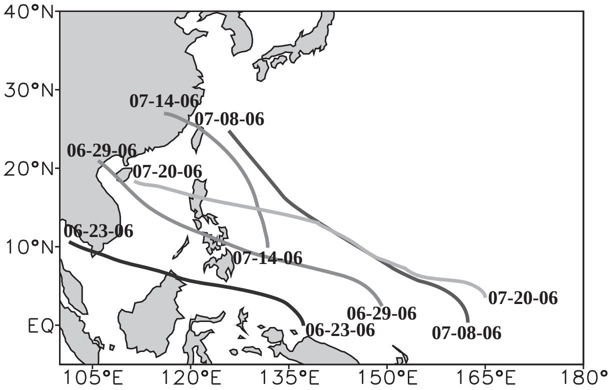

Fig. 2. The positions and dates of monsoon trough axes during June and July 2006, identified using the 850 hPa low-pass filtered winds.

3. TC formation within monsoon troughs

TC formation events within MTs are identified every six hours in this study. During the period 2000–10, 91 TCs are found to form in MTs in May–October, accounting for 43.1% of the total TC formation events. On average, 8.3 TC formation events are associated with MTs per year, with a maximum of 11 TCs in 2008 and a minimum of 6 TCs in 2006. Gao and Li (2011) defined a multiple TC formation event as a process in which two successive TCs form within three days, with the distance between them being less than 4000 km, and they found that the eastward-extending WNP MT favored multiple TC formation events. Based on their definition, 36 TCs are involved in such multiple TC formation events, accounting for 39.6% of the TCs associated with MTs.

During the six-month season, the monthly frequency of TC formation within the MT reaches its maximum in August (Fig. 3a). However, compared to the total TC formation frequency, the percentage of TC formation within the MT increases from May (44.4%) to June (70.6%) and then shows a decreasing trend after July. While more than 50% of TCs formed in MTs during June–July, the percentage becomes less than 50% during August–October. In particular, only 12.9% of TCs formed within MTs in October. This agrees with previous studies that MTs occur mainly from early or middle May to late September (e.g., Murakami and Matsumoto, 1994; Lau and Yang, 1997; Wu and Zhang, 1998; Hsu et al., 1999; Zhang et al., 2002). We also calculate MT active days for each month (Fig. 3b). MT active days are days with MT activity in their low-frequency wind fields. It is clear that the decreasing percentage of TC formation in MTs after July is accompanied by a decreasing number of MT active days.

We find that the percentages of TC formation in MTs are much lower than those in previous studies (Briegel and Frank, 1997; Ritchie and Holland, 1999; Molinari and Vollaro, 2013). Ritchie and Holland (1999) found that 71% of TCs formed within MTs, including 42% within the monsoon shear region and 29% within the confluence zone. In Molinari and Vollaro (2013), 73% of all July–November TCs formed within MTs during the period 1988–2010, and the percentage varied interannually from as low as 50% to nearly 100%.

As mentioned above, the difference in the percentage may result from the different approaches for identifying monsoon troughs and the associated TC formation. Since we have difficulty in reproducing the results from Briegel and Frank (1997) and Ritchie and Holland (1999), we focus here on a comparison with Molinari and Vollaro (2013).

Molinari and Vollaro (2013) defined an MT as the contiguous region with positive long-term mean July–November 850 hPa relative vorticity. Their analysis region ranged from 122°E to 180°. To understand how the different approaches can affect the results, we first use the approach in Molinari and Vollaro (2013) to identify the number of TCs that formed in MTs. To avoid a possible influence of the difference in datasets, both the ERA-Interim reanalysis data and the FNL data from 2000 to 2010 are used. The former dataset was used in Molinari and Vollaro (2013).

When we use the approach in Molinari and Vollaro (2013), the TC formation percentages based on the ERA-Interim reanalysis data and the FNL data are 58.8% and 58.3%, respectively, both of which are higher than the 43.1% established by our approach. Table 1 shows the monthly frequency of TC formation events identified with the approaches used in this study and in Molinari and Vollaro (2013). The TC formation events identified from the two datasets using the method of Molinari and Vollaro (2013) are nearly the same (Table 1), suggesting that the difference in the TC formation percentage is not a result of the different datasets.

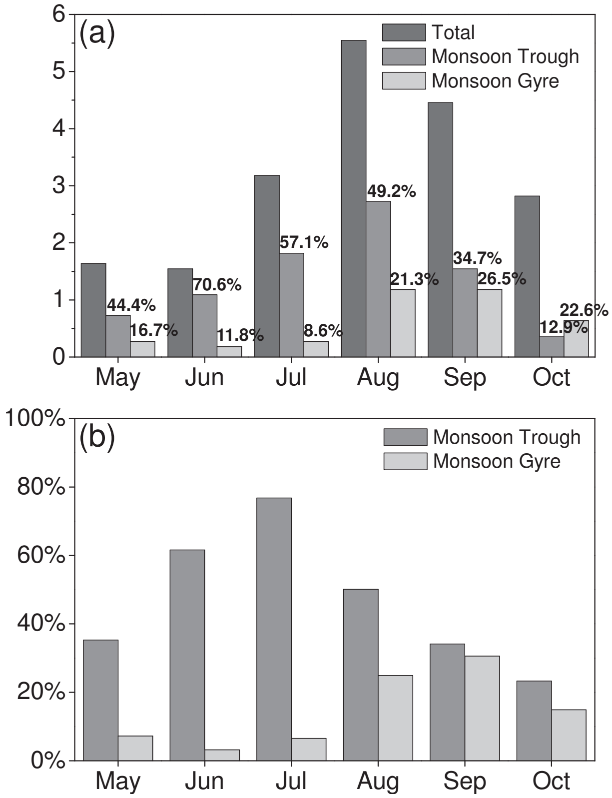

Fig. 3. Monthly frequencies of (a) all TC formation events (dark gray) and those formed in monsoon troughs (gray) and monsoon gyres (light gray) per year and (b) percentages of monsoon trough (gray) and monsoon gyre (light gray) active days for each month during 2000–10.

However, the monthly percentages of TC formation in MTs from our approach are very different from the approach in Molinari and Vollaro (2013), especially in September and October. While 34 and 19 TCs are identified to form within the climatological mean MT by the approach of Molinari and Vollaro (2013), our approach identifies only 17 and 4 TCs in September and October, respectively.

Figure 4 shows a comparison of TC formation events identified with the two different approaches. While some TC formation events (black) are identified by both approaches, a considerable number of TC formation events are counted only by one or the other of the two approaches. It is clear that TC formation events in the South China Sea (west of 120°E) are not counted by the approach of Molinari and Vollaro (2013). In addition, Fig. 4 indicates that TC formation events (green) that are counted by the approach of Molinari and Vollaro (2013) are excluded in our approach, in particular after August. Among the excluded TC formation events, further analysis shows that half of them formed in monsoon gyres.

Wu et al. (2013) recently indicated that, over the WNP, 19.8% of TCs formed in monsoon gyres in May–October during the period 2000–10, but the contribution of monsoon gyres cannot be distinguished from the MT defined in Molinari and Vollaro (2013). That is, the TC formation events from the approach of Molinari and Vollaro (2013) include those within monsoon gyres. If the percentage of TC formation events within monsoon gyres is added, we have 62.9% of TCs that form in both MTs and monsoon gyres. As shown in Fig. 3a, the percentage of TC formation in monsoon gyres is more than 20% in August–October. The increased percentage is consistent with the increase in monsoon gyre active days in these months (Fig. 3b). Except for October (35.5%), the combined percentage ranges from 61.1% in May to 82.4% in June, which is comparable to those in previous studies.

Table 1. Monthly frequency of TC formation in monsoon troughs identified with low-pass filtered fields and monthly mean fields in May–October during 2000–10. For comparison, the monthly frequency of TC formation in monsoon gyres (Wu et al., 2013) and the monthly frequency of TC formation in monsoon troughs identified from the ERA-Interim dataset are also shown in parentheses in the first and second rows, respectively.

	May	June	July	August	September	October
Filtered Fields	8 (3)	12 (2)	20 (3)	30 (13)	17 (13)	4 (7)
Monthly Fields	9 (9)	9 (10)	16 (18)	35 (35)	35 (34)	19 (19)

Figure 5 shows the composited 850 hPa low-frequency wind field for the MTs at the TC formation time. Ritchie

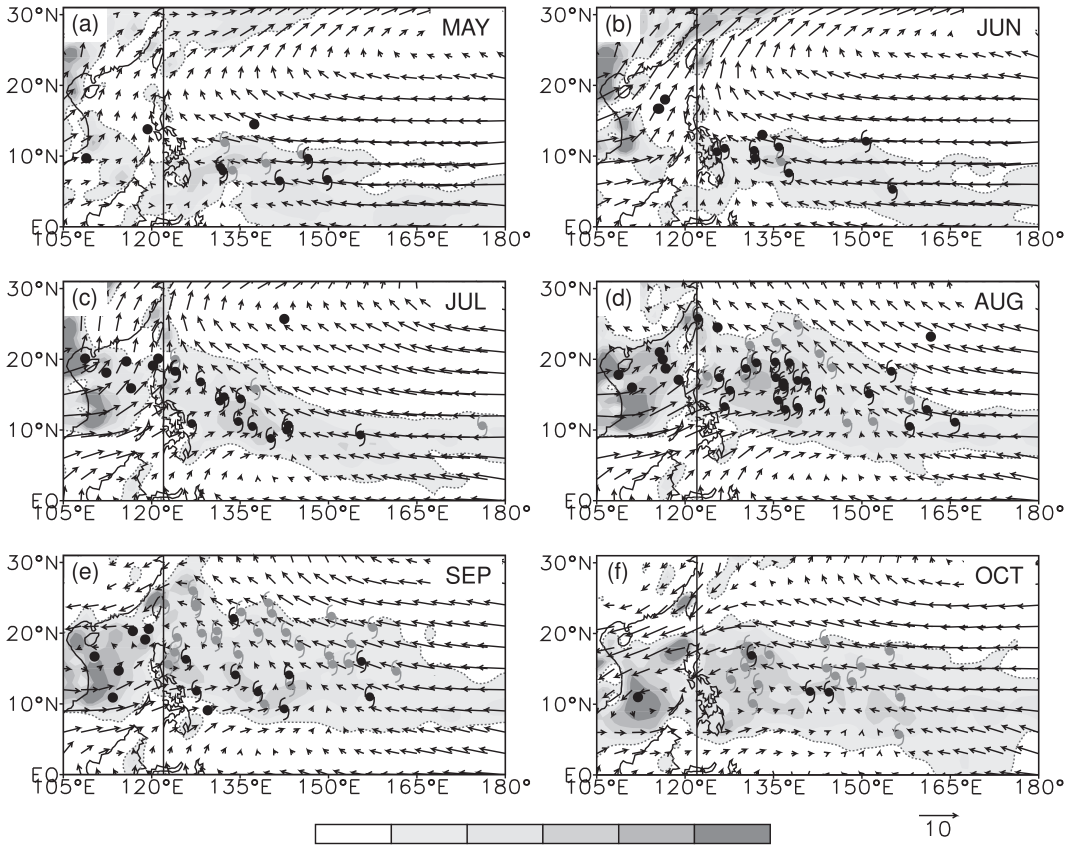

Fig. 4. The mean 850 hPa relative vorticity (10^{-6} s^{-1}, shaded for positive values) and mean 850 hPa winds (vectors, m s^{-1}) during 2000–10 using the unfiltered FNL data in (a) May, (b) June, (c) July, (d) August, (e) September and (f) October. The blue and green typhoon symbols indicate the formation locations of tropical cyclone (TC) centers based on our approach and the method of Molinari and Vollaro (2013), respectively. The black typhoon symbols indicate the formation locations of TC centers recognized by both methods.

and Holland, (1999) found that 29% of TCs formed within the confluence zone, while 42% of the TC formation events occurred within the monsoon shear region. As shown in Fig. 5, nearly all of the TC formation events occurred in the monsoon shear region. The difference may result from the contamination of synoptic-scale systems, such as TCs and wave trains, which were included in Ritchie and Holland (1999). In the following section, we show that the region favorable for TC formation is associated with the favorable large-scale conditions for TC formation.

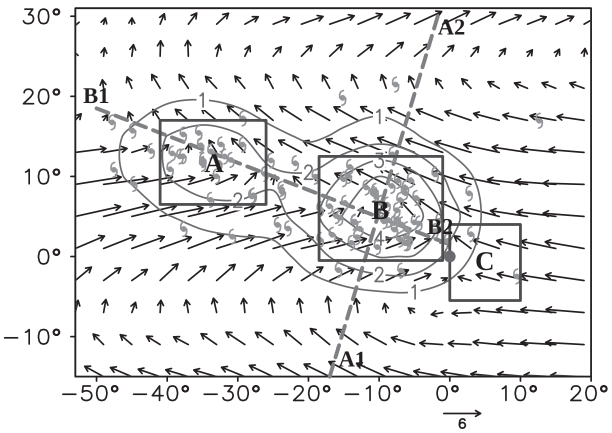

Fig. 5. Composited 10-day low-pass filtered 850 hPa wind field (vectors, m s^{-1}) and TC genesis frequency (contours) at the TC formation time for all the monsoon troughs. The dots indicate the reference centers, and the typhoon symbols the TC centers. Rectangles A, B and C indicate the regions of different TC genesis frequency.

4. Large-scale environment for TC formation

In order to understand why the monsoon shear region is favorable for TC formation, we conduct a composite analysis of the MT structure of the selected 91 samples during the period 2000–10. In agreement with previous studies (Sadler, 1967; Gray, 1968; Ramage, 1974; Gray, 1975; Frank, 1987; Chia and Ropelewski, 2002; Harr and Chan, 2005), the monsoon shear region is associated with strong low-level cyclonic relative vorticity, high mid-level relative humidity, and relatively weak vertical wind shear, which are favorable for TC formation.

Figure 6a shows the relative vorticity and zonal wind component across the axis of the composited MT (A1–A2). As shown in Fig. 5, the cross section represents the most favorable region for TC formation, about 1000 km west of the reference point. The positive relative vorticity associated with the MT is confined to a narrow region of about 1200 km in width, extending to about 350 hPa. On the equatorward side are the westerly monsoon winds, covering about 1200 km in width below 600 hPa. On the poleward side, the easterly trade winds cover a wider region and extend throughout the troposphere. In agreement with observations, it is suggested that TCs that form within the MT are generally steered westward by the mean deep-layer mean easterly flow.

Figure 6b shows the cross section of relative vorticity and relative humidity along the MT axis at the time of TC formation (B1–B2 in Fig. 5). The maximum relative vorticity occurs around 850 hPa and the positive relative vorticity is confined in the middle and lower troposphere (below 500 hPa). Consistent with the high TC formation rate, as shown in Fig. 6b, the region with high relative vorticity and relative humidity occurs in the east part of the shear region.

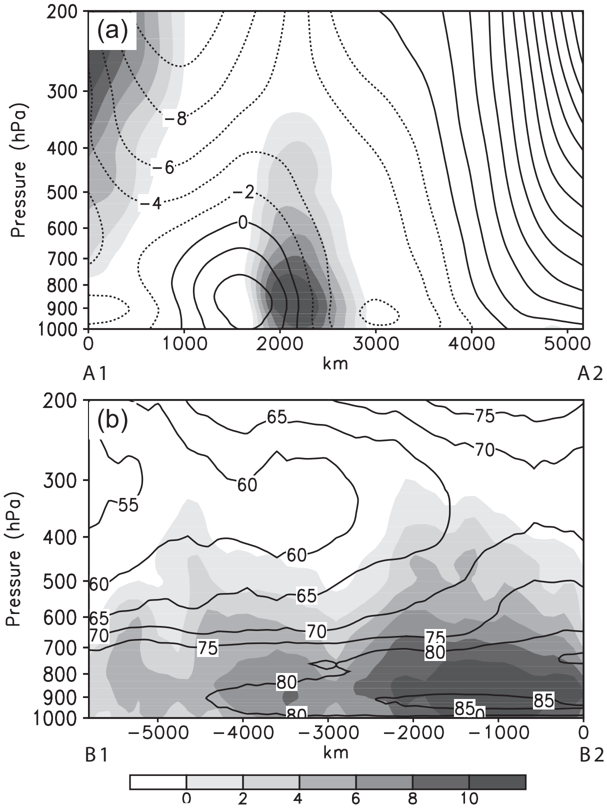

Fig. 6. Vertical profiles of the composited 10-day low-pass filtered (a) zonal wind components (contours, m s^{-1}), (b) relative humidity (contours, %) and (a, b) relative vorticity (shaded, 10^{-6} s^{-1}) for all the monsoon troughs (a) along the dashed line A1–A2 in Fig. 5 and (b) along the dashed line B1–B2 in Fig. 5 at the TC formation time.

Figure 7a shows the composited vertical wind shear field between 200 hPa and 850 hPa at the TC formation time. The environmental vertical wind shears are weak near the MT axis. Most of the TCs formed in weak vertical wind shear of less than 12.5 m s^{-1}. To further understand the spatial distribution pattern of TC formation in the MT, we compare the vertical profiles of relative vorticity, zonal wind, and relative humidity in three selected regions. As shown in Fig. 5, Regions A and B are in the shear-line region, where there is the most TC formation events, while Region C is in the confluence region, featuring less TC formation. Compared to Regions A and B, Region C is characterized by weaker low-level relative vorticity (Fig. 8a), which is unfavorable for TC formation (Gray, 1968, 1975). But there is not much difference in the mid-level relative humidity between Regions A, B and C (Fig. 8c).

A significant feature of Region C is the westerly zonal

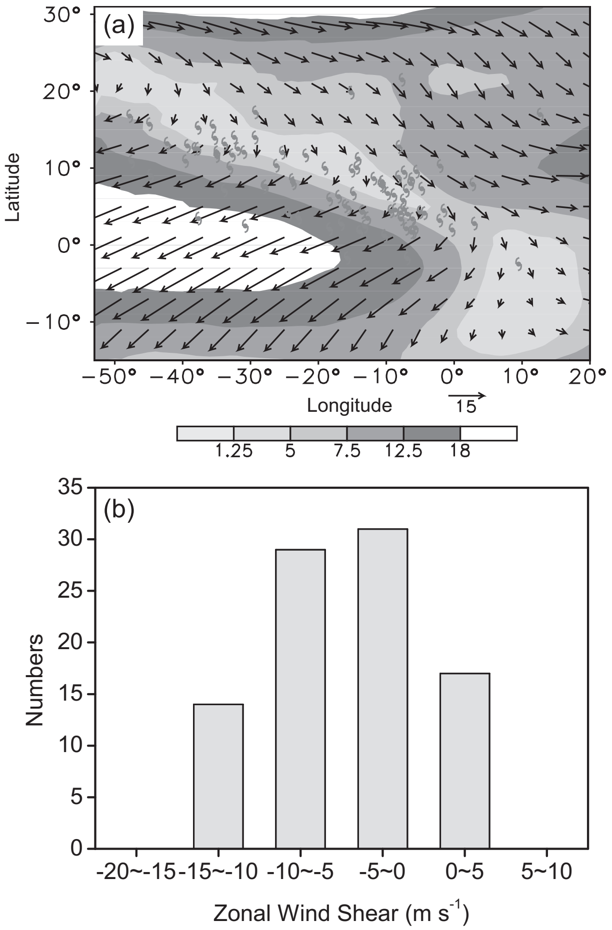

Fig. 7. (a) The composited 10-day low-pass filtered vertical wind shears (m s^{-1}) between 200 hPa and 850 hPa for all the monsoon troughs at the TC formation time, and (b) the frequencies of TC formation events in the monsoon trough during 2000–10 in different low-frequency zonal wind shears between 200 hPa and 850 hPa. The shading indicates vertical wind shear weaker than 18 m s^{-1}; and the typhoon symbols indicate the relative positions of TCs to monsoon troughs.

vertical shear (Fig. 8b). In a well-known idealized modeling study, Kurihara and Tuleya (1981) showed that mean easterly vertical wind shear is more favorable for TC formation than westerly vertical wind shear. In order to examine the favorableness of TC formation in the easterly vertical wind shear, we plot a histogram of frequencies of zonal wind shear in bins of 5.0 m s^{-1} for all of the formation events in MTs (Fig. 7b). The shear between 200 hPa and 850 hPa is calculated based on individual TC events at TC formation time with the filtered winds. While the TCs can form only in westerly zonal shear of less than 5.0 m s^{-1}, most formation events occur in easterly zonal shear, even as high as 10.0 m s^{-1}. Figure 9 shows the composited three-dimensional structure of MTs. The low-level MT is overlaid by the northeasterly flows associated with the South Asia high at 200 hPa. This is why most of the formation events occurred in the easterly zonal shear.

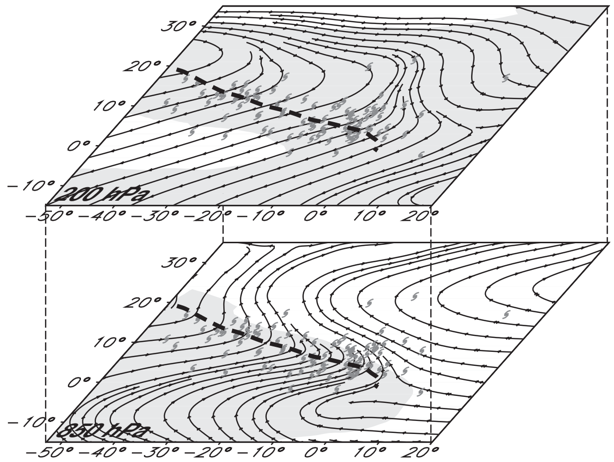

Fig. 9. The vertical configurations of TC formation in the monsoon trough. The shading in the upper panel indicates the smaller vertical wind shear, while that in the lower panel indicates the easterly zonal shear. The typhoon symbols indicate the TC locations at the TC formation time. The bold dashed lines indicate the monsoon trough lines.

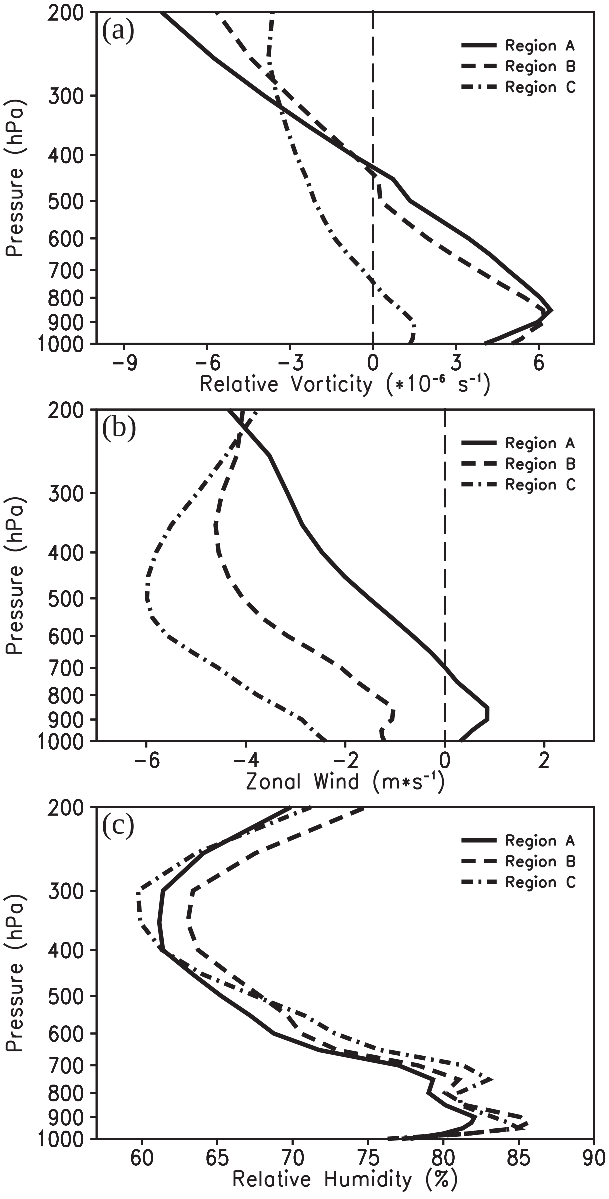

Fig. 8. Vertical profiles of the regional averages of the (a) relative vorticity, (b) zonal winds, and (c) relative humidity for the regions A, B and C in Fig. 5.

Although this result is in agreement with the idealized modeling result in Kurihara and Tuleya (1981), the favorableness of easterly zonal shear in MTs may be associated with other large-scale conditions and the initial synoptic-scale tropical disturbances that always precede TC formation. Using a multilevel, nonlinear baroclinic model, Li (2006) suggested that the synoptic wave train in an MT may result from instability of the environmental flow. His numerical experiments indicate that an easterly shear can lead to a faster growth and northwestward propagation of synoptic wave trains than a westerly shear. Ge et al. (2007) examined the effect of vertical shear on wave trains induced by TC energy dispersion and found that an easterly (westerly) shear favors the growth of the wave train in the lower (upper) troposphere. Wang and Xie (1996) found that vertical wind shear can significantly affect the Rossby wave and westward Yanai wave. While westerly shear favors trapping of these waves in the upper troposphere, easterly shear tends to confine them to the lower troposphere. In all of the 91 TC formation events, we find that 38 cases were clearly associated with synoptic wave trains. We should mention that the resulting wave trains or tropical disturbances may provide a synoptic environment to counter the low-frequency vertical wind shear and enhance the other favorable conditions for TC formation. Further investigation is called for in this respect.

Ferreira and Schubert (1997) and Li (2006) suggested that the initial disturbances for TC formation may arise from the instability of the environmental flow. Based on numerical simulations, Li (2006) argued that the origin of the synoptic wave train arises from both the dynamic effect of the MT flow and the thermodynamic effect of the convective heating feedback. In order to examine the possible role of barotropic instability, the meridional gradients of the absolute vorticity of the composited MT were calculated. There are indeed isolated regions with the sign reversal of the absolute vorticity gradient (figure not shown). This suggests that the barotropic instability of the MT flow may play a role in TC formation in MTs.

5. Summary

Unlike previous studies in which the MT was subjectively defined (Briegel and Frank, 1997; Ritchie and Holland, 1999) or treated as a geographical region in terms of monthly mean 850 hPa relative vorticity (Wu et al., 2012; Molinari and Vollaro, 2013), this study re-examines the TC formation in the MT over the WNP by treating it as a large-scale background for the activity of synoptic systems, including wave trains and TCs. Given the possible distortion of the large-scale pattern composited with respect to TC centers in previous studies due to large variation in the relative positions of TC formation within MTs (e.g., Briegel and Frank, 1997; Ritchie and Holland, 1999), the composite in this study is conducted based on a reference point in the confluence zone where both the zonal and meridional wind components are zero with positive vorticity.

During the period 2000–10 in May–October, 91 TC formation events are identified in MTs, with a seasonal average of 8.3 formation events or 43.1% of all TC formation events in the WNP. The percentage of TC formation in MTs ranges from 12.9% in October to 70.6% in June. The resulting percentage of TC formation events in MTs is much lower than those in previous studies (e.g., Briegel and Frank, 1997; Ritchie and Holland, 1999; Molinari and Vollaro, 2013). The difference may result from the different approaches used in identifying MTs and the associated TC formation events. In addition, we argue that previous studies may have included TC formation events in monsoon gyres (Molinari and Vollaro, 2013). Wu et al. (2013) found that 19.8% of TCs formed in monsoon gyres in May–October during the period 2000–10. Except for October (35.5%), the combined percentage in MTs and monsoon gyres ranges from 61.1% in May to 82.4% in June, which is comparable to those in previous studies.

Nearly all of the TC formation events occur in the MT shear region, while previous studies indicated that a considerable number of TCs formed in the confluence zone. The shear line region is associated with stronger low-level relative vorticity, easterly vertical shear of zonal wind, and barotropic instability. The favorableness of easterly shear agrees with the observational analysis in Lee (1989) and the modeling results in Kurihara and Tuleya (1981). We argue that the favorableness in the WNP may be associated with the development of precursor tropical disturbances in the MT that are necessary for TC formation.

In the last decade or so, some studies have found TC genesis frequency to be related to long-term atmospheric oscillations, such as the North Pacific Oscillation (NPO) and the Antarctic Oscillation (AAO), and the sea ice cover over the North Pacific (e.g., Wang and Fan, 2006; Wang et al., 2007a, 2007b). In those studies, the influences were associated with the changes in the large-scale environmental conditions for TC formation. It is possible that they may affect TC formation through changing the orientation and zonal extension of the monsoon trough. Further investigation in this field is needed.

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