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The Role of Trade Wind Surges in Tropical Cyclone Formations in the Western North Pacific

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ABSTRACT
A total of 40 out of 531 tropical cyclones that formed in the western North Pacific during 1986–2005 have accompanied trade wind surges located 5°–15° latitude to the north of the pretropical cyclone disturbance centers. Composite and empirical orthogonal function analyses indicate that the trade wind surges are related to a midlatitude eastward-moving high pressure system often found during the East Asian winter monsoon. Therefore, these trade wind surge tropical cyclones tend to occur in late season (with one-third of them in December), and at lower latitudes (7° latitude lower than the climatological average formation position).

The evolution of mesoscale features during formation of trade wind surge tropical cyclones is examined. Various satellite datasets show similar mesoscale patterns during their formations. A few convective lines form by convergence between the trade wind surges and the strengthening cyclonic circulation associated with incipient vortex within the 24 h before formation. Some mesoscale convective systems are embedded in the convective line with lifetimes of about 5 h, and these are illustrated through case studies. Formations usually occur when the trade winds start to decrease in magnitude and a short period after the major episodes of convection in the convective lines and mesoscale convective systems. The relationships between the temporal variability of synoptic-scale trade wind surges, the mesoscale features, and associated tropical cyclone formations are discussed.

1. Introduction
One of the features that distinguish tropical cyclone (TC) formations in the western North Pacific (WNP) from those in the other basins is the wealth of different synoptic patterns and associated dynamics responsible for the formations. For example, Ritchie and Holland (1999) identified five low-level dynamical patterns of formation in the WNP, which are monsoon shear line, monsoon gyre, easterly wave, confluence region, and energy dispersion. Among these patterns, the monsoon shear line accounts for the largest number (42%) of cases. This is due to the fact that the monsoonal westerlies/southwesterlies and trade easterlies compose the basic synoptic setting of the monsoon trough (or intertropical convergence zone) in the basin with abundant low-level relative vorticity, which is one of the necessary conditions for TC formations (Gray 1968; 1998). In addition, Cheung (2004) found low vertical wind shear at the monsoon shear line that is again favorable for formation, and the seasonal migration of the shear line in the meridional direction modulates the average latitude of formation in each month.

Under the context of identifying mesoscale convective systems and convective features associated with TC
formations, Lee et al. (2008) classified six synoptic patterns in the WNP according to the low-level wind structure. Among the six patterns, the monsoon-related ones that consist of the monsoon shear, monsoon confluence, southwesterly flow, northeasterly (NE) flow, and coexistence of northeasterly (NW) and southwesterly (SW) are considered generalization of the monsoon shear line pattern in Ritchie and Holland (1999). In particular, the formations with NE flow pattern [Fig. 2b of Lee et al. (2008)] are all in the boreal winter months from October to March in the following year. In the classification procedure of Lee et al. (2008) the 925–850-hPa areal-average zonal and meridional winds have to be persistently over 5 m s$^{-1}$ prior to formation for this pattern, and hence some of the TC cases involved are likely associated with strengthening of the trade easterlies (i.e., the trade wind surge). Association of trade wind surge with TC formation has been generally discussed in the past (Riehl 1948; Lee 1986). To improve over these early studies, the focus of this study is to establish the climatology of TC formations associated with trade wind surges, to examine how variability of trade wind surge modulates TC activity, and to clarify the role of trade wind surge during TC formation in the synoptic scale. Moreover, based on some high-resolution remote sensing data that are only available in recent decades, mesoscale features in such wind surges are discussed.

Being one of the major wind systems in the Pacific, the climatology and interannual variability of trade winds have been investigated from decades ago (e.g., Barnett 1977). Through empirical orthogonal function (EOF) analysis, Barnett (1977) found that the region $10^\circ$–$20^\circ$N, $150^\circ$E–$150^\circ$W is the quasi-permanent, core region of trade wind field in the North Pacific because this region has the largest loading in the first EOF mode, which explains over 90% of variance in zonal wind. The part of this region near the WNP is an active TC formation region and contains most of the TC cases in this study. Although the second EOF mode of Barnett (1977) explains only a few percent of the variance in zonal wind, the time series of the amplitude indicates seasonal shift of the trade wind system and the subtropical high. Interestingly, the loading pattern of this mode consists of strong trade winds west of $150^\circ$E and east of $140^\circ$W. This bimodal characteristic may also affect distribution of TC formations associated with trade wind surges in the WNP.

The organization of this paper is as follows. The data sources and methodology used in this study are described in section 2. In section 3, the climatological features of the selected trade wind–related TC formation cases are highlighted and compared with those not under influence of trade winds. The mesoscale features during formations as revealed from high-resolution satellite data is depicted in section 4. The summary and conclusions follow in section 5.

2. Data and case selection

a. Data

This study includes analysis of the 531 TC formations during the years 1986–2005 that occurred in the region $0^\circ$–$30^\circ$N, $122^\circ$E–$180^\circ$E. Most of the diagnostics utilize the 6-hourly global analysis from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis products. The horizontal resolution is 2.5$^\circ$ latitude–longitude with 17 mandatory pressure levels from 1000 to 10 hPa. Detailed descriptions of the NCEP–NCAR reanalysis dataset can be found in Kistler et al. (2001). Although the resolution of this global dataset is low, the wind field features of interest here are over a domain of hundreds of kilometers, and thus should be able to be resolved by the NCEP–NCAR reanalysis data.

The TC formation dates and locations are based on the annual tropical cyclone reports (ATCR) and best tracks issued by the Joint Typhoon Warning Center (JTWC). A TC formation alert (TCFA) is usually issued by the JTWC whenever interpretation of satellite imagery and other observational data suggest that the formation for a tropical depression (12 m s$^{-1}$ maximum sustained surface winds) is likely within 24 h (ATCR 1986–2005). In this study, TCFA has been used as TC formation reference time because the system should be undergoing the formation process at this time period and the changes of environmental condition before this time period might be important to TC formation. Occasionally there are several TCFA released, and the last TCFA will be taken as the formation reference time. Subsequently, environmental data at the first synoptic time after the TCFA near the disturbance is taken for composite analysis.

To identify the mesoscale features during formation periods, high-resolution satellite data, including the Quick Scatterometer (QuikSCAT) level-3 daily surface oceanic winds, the Tropical Rainfall Measurement Mission (TRMM) Microwave Imager (TMI) cloud liquid water data, and hourly infrared (IR) temperature from the Geostationary Operational Environmental Satellite-9 (GOES-9) from the National Oceanic and Atmospheric Administration (NOAA) and Multifunctional Transport Satellite (MTSAT) from the Japan Meteorological Agency (JMA). QuikSCAT products provide both wind speed and direction, which cover global oceans with a resolution of 0.25$^\circ$ latitude–longitude. The TMI data cover the tropical region between $40^\circ$S and $40^\circ$N and provide 10-m
wind speed (11 and 37 GHz), sea surface temperature, atmospheric water vapor, cloud liquid water, and precipitation rates with a horizontal resolution of 0.25° latitude–longitude. Furthermore, IR channel-1 (IR1, wavelength 10.3–11.3 μm) images are used to examine convection activity. The IR1 cloud-top temperature has a resolution of 0.05° latitude–longitude and covers 20°S–70°N, 70°–160°E. This IR dataset includes three different satellite platforms serving in different periods: Geostationary Meteorological Satellite-5 (GMS-5) from June 1995–May 2003, GOES-9 from May 2003–July 2005, and MTSAT-1R from July 2005 until present. These IR1 images are obtained from a digital archive in the Kochi University of Japan. The IR1 image closest in time to the formation is assumed to be representative of the convective precipitation centers and can serve to reveal the unique magnitude of the trade wind surges.

For comparison purpose, there are 117 TC cases that occurred during October–December but do not satisfy both criteria, and they are designated no trade wind surge formation cases. The statistics of synoptic patterns associated with TC formations in Lee et al. (2008) show that the patterns with strong easterlies north of the formation center (NE, NE–SW, and easterly wave) account for over 75% of all cases during October–December. Therefore, these TCs without trade wind surge have similar environmental flow pattern north of the formation centers and can serve to reveal the unique magnitude of the trade wind surges.

3. Climatology of TC formation associated with trade wind surges

a. Temporal and spatial distributions

The average magnitude of easterlies for all the 45 selected TC cases in the domain indicated in Fig. 1 increases from 8.7 m s\(^{-1}\) at −72 h to 11.6 m s\(^{-1}\) at TCFA, and decreases as the TCs continue to move westward after TCFA (Fig. 2). The standard deviations at all times before TCFA are around 2 m s\(^{-1}\), and in many of the cases the average easterlies are substantially above the climatological averages. Statistical chi-square tests indeed show that they are significantly different with confidence level over 99%. Examination of the synoptic patterns of the selected cases reveals that five of them are embedded in synoptic patterns significantly different from those of the others. These five cases are excluded...
from further analysis because the robustness of the subsequent composites of environmental conditions will be much affected. For the remaining 40 cases (Table 1), 67.5% of them are in the late season (October–December) and no occurrence is in the first 2 months of a year (Fig. 3). The monthly formation rate of trade wind surge-related TCs with respect to all formation cases increases from 8.1% (6 out of 74) in October to 27.9% (12 out of 43) in November, then to 33.3% (9 out of 27) in December. It is intuitive to consider that because of the trade wind surges, the associated TC formations are more likely to undergo rapid development and attain higher intensities. Examination of the 40 selected cases in Table 1 indicates that 16 of them attain supertyphoon (130 kt) intensity, and such percentage of occurrence (40%) is much higher than that usually found annually (13%–14% based on JTWC best tracks). However, the average period for these TC formation cases from TCFA to tropical storm stage (34.3 h, standard deviation of 21.0 h) is actually longer than those cases without trade wind surges (28.9 h, standard deviation of 23.7 h). In addition, the average period from tropical storm to typhoon stage for the trade wind surge cases is also longer (48.6 h, standard deviation of 24.9 versus 42.9 h, standard deviation of 20.9 h). Given these large standard deviations, the differences between the trade wind surge cases and those without for the TCFA to tropical storm period and the tropical storm to typhoon period are only statistically significant at a low confidence level of about 75%. Since the scope of this study focuses on TC formation, the role of trade wind surges in intensification is not further explored.

On spatial distribution, the TC formation locations associated with trade wind surges are mostly between 5° and 10°N (Fig. 4), which are just south of the core latitudinal band of 10°–20°N for trade wind surges as discussed earlier in section 1. The average position of the 40 trade wind surge TCs (7.4°N, 153.0°E) is east and south of the climatological average position (14.5°N, 145.2°E). In the zonal direction, these trade wind surge TCs spread from about 130° to about 170°E. This large spread in longitudes of their formation positions is likely due to the eastward-propagating disturbances in the trade winds from the Indian Ocean to the Pacific as identified in Barnett (1983; 1984). Barnett discussed that these disturbances are combination of a standing wave pattern associated with the Walker cell (with maxima in the Indian and western Pacific) and an equatorially trapped Kelvin wave. Thus, TC formation is possible at various longitudes when these disturbances encounter favorable environmental conditions south of them.

b. Composite trade wind surge

Because the QuikSCAT oceanic winds are not available at regular times, the NCEP–NCAR reanalyses are used to compute composites of TC formation associated with trade wind surges. The center of composites is taken as the 1000-hPa circulation center of the disturbance and the composites are prepared for every 24 h from −72 to +48 h. (When the 1000-hPa center is not clearly identified, the 850-hPa vorticity center is used instead.) The 850–925-hPa average composite flow shows that the trade winds are accompanied by an eastward-moving high pressure system located at about 15° (22°) latitude poleward of the strong trade wind region (pre-TC center, Fig. 5). The maximum wind speed of trade wind increases substantially from 12 m s⁻¹ at −72 h to 16 m s⁻¹ at −24 h when the high pressure system passes by. Note that the area with trade winds greater than 12 m s⁻¹ extends over 2000 km in longitude. This synoptic setting agrees with the monthly distribution of TC formations associated with trade wind surges, which mostly occur during the late season when the midlatitude high pressure systems are more active.

It is also notable from Fig. 5 that while the pre-TC disturbance develops, the background relative vorticity elongates in the east–west direction but without substantial increase. The trade wind pattern indicates that the cyclonic horizontal wind shear contributes a lot to the generation of relative vorticity in a large area. As a feedback mechanism, the pressure gradient between the midlatitude high pressure system and the low pressure system to the south will be increased when they are
in phase, which then intensifies the trade winds. The relative vorticity of the incipient TC disturbance shows obvious increase between 24 h to TCFA while the area of maximum wind speed in the trade wind zone contracts to the disturbance scale (Figs. 5c,d).

Vertically, the strong trade winds are confined below 800 hPa at 72 h (Fig. 6a). Then the altitude of the maximum trade wind moves slightly upward from 900 hPa at 48 h to 850 hPa at 24 h (Figs. 6b,c). As seen in Fig. 5, the horizontal scale of the strong trade wind region (greater than 12 m s\(^{-1}\)) also increases from about 10° to 15° latitude in this period. This poleward extension of strong low-level easterlies indicates that the trade wind surges intensify prior to TC formation (that is closely related to variability of the subtropical high, see discussion in section 3d in the following), but this intensification may be partially due to that of the incipient TC only. After taking into account the speed of the pre-TC disturbance, it is found that the relative wind speed north of system center increases from 6 m s\(^{-1}\) at 48 h to 12 m s\(^{-1}\) at TCFA while that at southern side shows little increment. At TCFA, the TC’s strong relative vorticity becomes a column structure and extends farther upward, and so do the strong easterlies north of the TC (Fig. 6d).

Examination of the time series of the area-average (within a system-centered 8° latitude × 8° longitude domain) relative vorticity for the 40 trade wind surge TCs indicates that major intensification occur between 72 to 24 h (Fig. 7). In the same period, the easterlies at 925 hPa increase significantly from 4 to 10 m s\(^{-1}\) (Fig. 8b). The increase in total wind speed is mostly contributed by the zonal wind component because that for the meridional wind speed at the same levels is relatively

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small (Figs. 8a,c). It has to be noted that the average growth rate of relative vorticity during the 3 days prior to formation is not a linear process. It is $3.4 \times 10^{-6} \text{ s}^{-2}$ from $-72$ to $-48$ h, further increases to $4.1 \times 10^{-6} \text{ s}^{-2}$ from $-48$ to $-24$ h, but reduced substantially to $0.5 \times 10^{-6} \text{ s}^{-2}$ during the 24 h before TCFA (Fig. 7). This nonlinear trend suggests that the trade wind surges mainly enhance the favorable environment for TC formation during the early development stage of the disturbances but some other factors may also contribute to the formation in the later stage. In addition, the meridional winds are northerlies between 950 and 700 hPa and southerlies above 700 hPa (Fig. 8c). Because northerlies can enhance relative vorticity of the disturbances, this confirms that the development of these trade wind surge TCs occur at the low levels below 700 hPa and the cyclonic circulation extends upward gradually into the midlevels.

The composite 850-hPa relative vorticity and vertical wind profiles for the 117 TC formations during October–December without trade wind surge are also examined. In contrast to those accompanied with trade wind surges, both the easterlies and northerlies are much weaker below 700 hPa (Fig. 9). As a consequence, the average growth rate of the low-level relative vorticity is much

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**Fig. 4.** Spatial distribution of TC formations associated with trade wind surges (solid circle) and their average position (solid square). Open square represents the 20-yr climatological average formation location.

**Fig. 5.** Composite 850–925-hPa flows for trade wind surge TCs at (a) $-72$, (b) $-48$, (c) $-24$ h, and (d) TCFA. The system center is located at (0, 0). The heavy contours indicate positive relative vorticity (interval: $1 \times 10^{-5} \text{ s}^{-1}$) and the shaded regions are wind speeds greater than $10 \text{ m s}^{-1}$ (interval: $2 \text{ m s}^{-1}$).
lower for these 117 TCs, which increases steadily throughout the formation process but with a value of only about $1.6 \times 10^{-5} \text{ s}^{-1}$ at TCFA (Fig. 7). Similar to that performed for the average magnitude of easterlies, chi-square tests indicate that the average relative vorticity values for the trade wind surge cases are significantly larger than those without surge with a 90% confidence level from $-24$ h up to TCFA.

**c. Relationship with intraseasonal variability**

As can be seen from their climatology, the trade wind surge TCs largely occur during the late season when the Madden–Julian oscillation (MJO) is more active than that in summer. To explore the relationship between intraseasonal disturbances and the trade wind surge–related TC formation cases, the MJO index proposed by Wheeler and Hendon (2004) is examined. This MJO index was developed by performing EOF analysis on combined fields of upper- and lower-level zonal winds as well as outgoing longwave radiation. Among the 40 selected trade wind surge TCs, 10 occurred at MJO phases 6 and 7 as defined in Wheeler and Hendon (2004) when peak convection is over the western Pacific with collocated strong westerly anomalies [Fig. 9 in Wheeler and Hendon (2004)]. However, the average values of the real-time multivariate MJO series 1 (RMM1, principle component of the first EOF) and 2 (RMM2) for these 10 cases at TCFA are 0.07 and 0.98, respectively, which indicate weak MJO-enhanced convective period. This result is consistent with the composite flow of the trade wind surge TCs (Fig. 5) that shows no particularly strong westerlies.

![Fig. 6. North–south-oriented vertical cross section of the composite zonal wind magnitude greater than 10 m s$^{-1}$ (contour, interval: 2 m s$^{-1}$) and positive relative vorticity (shaded, interval: $1 \times 10^{-5} \text{ s}^{-1}$) for the trade wind surge TCs at (a) −72, (b) −48, (c) −24 h, and (d) TCFA.](image)

![Fig. 7. Time series of the composite average 850–925-hPa relative vorticity (unit: $1 \times 10^{-5} \text{ s}^{-1}$) within an 8° lon × 8° lat area with respect to the disturbance center of the trade wind surge TCs (solid) and 117 no trade wind surge TCs formations during 1986–2005 (dash).](image)
to the south of the pre-TC disturbance before the TCFA. Thus, only a portion of the TC formations associated with trade wind surges develop in MJO phases that possibly enhance the spinup process, but the degree of enhancement is small for the cases identified in this study. One of the uncertainties of the above analyses is that the structure of MJO is varying annually (e.g., with influences from the El Niño–Southern Oscillation), and this may affect the overall degree of correlation with the trade wind surge TC activity. Moreover, there are other intra-seasonal patterns such as the equatorial Rossby waves, which move westward and frequently induce convective features that are advected northward by the meridional background winds. Examples are TCs and gyres associated with these Rossby waves (Dickinson and Molinari 2002). These TCs and gyres may modulate the distribution of trade winds (Liebmann and Hendon 1990), but these extra factors are not analyzed in details in this study.

d. Origin of trade wind surges

Whereas the previous association of trade wind surges with subtropical systems is quite qualitative, EOF analysis of the 850–925-hPa geopotential height anomalies is performed to objectively examine this association. The EOF analysis is done on the geopotential height anomalies in a system-centered domain for all trade wind surge TCs at a particular time before TCFA. The explained variance of the first EOF mode ranges from about 30% to 45% at different times, and that for the second mode is about 15%–28%. Evolution of the first EOF mode depicts a system with a local maximum geopotential height at about 30° latitude to the north of the pre-TC center, and moving eastward with a speed of about 5° longitude day⁻¹ (Figs. 10a,b). This eastward propagation of the high pressure system first brings strong easterlies to the northwest quadrant of the pre-TC disturbance then enters the northeast quadrant. On the other hand, the second EOF mode shows a weak, semistationary negative anomaly in geopotential height that represents a trough located at about 30° latitude.
north of the pre-TC center (Fig. 10c). When these two modes are combined in the reconstruction of the original geopotential height, the first mode dominates such that only the ridge associated with trade wind surges is clearly revealed (Fig. 10d).

When EOF analysis is performed for all the 157 TC formation cases (with or without trade wind surges), the role of the first two modes almost switch. That is, the first EOF mode in this new analysis that explains about 58% of variance represents midlatitude trough variability, while the second mode that explains about 29% of variance represents subtropical high variability (not shown). Therefore, variability of synoptic systems north of the formation center is crucial to the TC formations in these three late-season months. Nevertheless, it has to be emphasized that these are storm-centered EOF analyses, and thus any transient features within fixed geographic domains cannot be revealed from these analyses.

4. Mesoscale features of TC formation associated with trade wind surges

As is mentioned briefly in the introduction, the TC formations associated with trade wind surges in this study likely belong to the NE synoptic pattern defined in Lee et al. (2008). The characteristics of the TCs that form in this pattern include occurrences at late season, strong easterlies poleward of the disturbances, and an anticyclonic circulation located about 20° latitude to the north of the disturbances. Moreover, the favorable distribution of MCSs for the NE-type TCs is in northeast and northwest quadrants.

Hourly GOES-9/MTSAT IR imageries, QuikSCAT oceanic winds, and TMI rainwater data are examined to analyze the mesoscale features of TC formations associated with trade wind surges. The QuikSCAT wind data and TMI rainwater data at times nearest to the hourly satellite imageries are used. In particular, Typhoon...
Bolaven (2005) is chosen as an example to illustrate the evolution of mesoscale features. The TCFA for Bolaven was issued at 2200 UTC 12 November, and from about 36 h before 0000 UTC 13 November there was a high pressure system moving southeastward from the Korean peninsula (Fig. 11). Such synoptic setting is similar to the first EOF mode of geopotential height depicted in Fig. 10, which consists of a high pressure system moving eastward.

Fig. 11. JMA surface weather map at 0000 UTC 13 Nov 2005. The low system located at 7°N, 133°E is the pre-Typhoon Bolaven (2005) disturbance. Symbols $H_{-36h}$, $H_{-24h}$, and $H_{-12h}$ indicate the locations of the high pressure system at 36, 24, and 12 h before the current time.
with a distance of about $25^\circ$ latitude to the north of the incipient disturbance, which was located east of the Philippines in this case of Typhoon Bolaven.

Thirty-six hours before the TCFA of Bolaven, an east–west-oriented convective line is observed at $7^\circ$–$9^\circ$N, $132^\circ$–$140^\circ$E (marked by A in Fig. 12). The IR satellite imageries also indicate that some strong convective cells were embedded in this line, which then developed further at $-25$ h (Fig. 12b) and extended southwestward at $-19$ h (Fig. 12c). QuikSCAT oceanic winds at 2042 UTC 11 November indicate patches of relative vorticity over $2.5 \times 10^{-5}$ s$^{-1}$ (maximum value over $10 \times 10^{-5}$ s$^{-1}$) within the convective line, and this area with large relative vorticity was at the northwest edge of a broad cyclonic circulation (marked with L in Fig. 12c). The lifetime of this convective line was nearly 24 h and then it dissipated when the strong trade wind area moved eastward slowly. At $-19$ h, convection concentrated at the western side of the previous convective line area (Fig. 12d).

Five hours later ($-14$ h), the surface incipient vortex can be observed at $5.5^\circ$N, $133^\circ$E that is at the western edge of the previous weak cyclonic circulation area (Fig. 13a). Strong relative vorticity patches with maximum values over $10 \times 10^{-5}$ s$^{-1}$ can be found near this incipient vortex. Because of the convergence between the strong northeasterlies and the cyclonic circulation of the incipient vortex, another convective line (marked by B in Fig. 13b) formed to the north of the strong vorticity center. This convective line B developed and rotated cyclonically in the subsequent 12 h but like convective line A eventually dissipated just before the TCFA of

FIG. 12. Cloud-top temperature lower than $-3^\circ$C (shaded, interval: $5^\circ$C) in the MTSAT enhanced IR imageries at (a) 1000 UTC ($-36$ h with respect to Typhoon Bolaven’s TCFA time), (b) 1600 UTC ($-30$ h), (c) 2100 UTC 11 Nov ($-25$ h), and (d) 0300 UTC 12 Nov 2005 ($-19$ h). Also shown in (a) and (c) are the QuikSCAT oceanic winds and derived relative vorticity (contour values are 2.5 and $10 \times 10^{-5}$ s$^{-1}$) at 0948 and 2042 UTC 11 Nov 2005, respectively. See text for symbols A and L.
Bolaven (Fig. 13c). At 0900 UTC 13 November (+11 h), major convection associated with Bolaven was located just east of the Philippines. But again, the cyclonic circulation of the disturbance merged with the trade winds to form a third convective line that extended eastward for about 5° longitude from Bolaven’s center (symbol C in Fig. 13c). Four hours later, convective line C extended farther eastward with several embedded mesoscale convective cells (Fig. 13d). It should be noted that although another strong convective cell formed at around 10°N, 143°E as shown in Fig. 13b, that cell eventually ceased to develop without the association with cyclonic circulation as in the case of Bolaven.

Similar synoptic and mesoscale features also are observed in three other trade wind surge TCs that are covered by available QuikSCAT and TRMM/TMI data. For example, Typhoon Nanmadol (2004) was also associated with a high pressure system moving eastward at about 25°–30° latitude north of the tropical depression that developed into Nanmadol (Fig. 14a). A southwest–northeast-oriented convective line (symbol A in Fig. 14b) identified by TRMM/TMI data with spatial scale of approximately 6° longitude × 2° latitude. This convective line rotated and decayed during the next 11 h. Meanwhile, because of the convergence between the cyclonic circulation of the pretyphoon disturbance and strong trade winds, another convective line (symbol B in Fig. 14c) formed in the northeastern quadrant with spatial scale of 5° longitude × 2° latitude at 16 h after TCFA. The two other TC cases are tropical storms 28°W (2001) and 31°W (2004), and again similar mesoscale features as in Typhoons Bolaven and Nanmadol are identified. However, since QuikSCAT dataset is not covering the essential formation periods of the other trade wind surge TCs, the features in particular the development of the line-shaped convection and development of associated
strong low-level vorticity patches as revealed in the above examples cannot be confirmed further.

5. Summary and conclusions

Among the 531 TCs that occurred in the WNP during 1986–2005, 40 cases were associated with trade wind surges during formation periods, which were mostly in the late-season months from October to December. Composites using the NCEP–NCAR reanalyses show that during the formation periods of these 40 TCs, the average trade wind increases from 12 to 16 m s\(^{-1}\) and are strongest at 850–925 hPa. The horizontal scale of the trade winds extends from 10° to 15° latitude and is located to the north of the pre-TC center. The analysis results indicate that the trade wind surge may be the key effect to vorticity generation that leads to the incipient vortex formation of these TCs. This occurs when the cyclonic shear vorticity at the southern edge of the trade wind zone increases with wind speed. In contrast, the zonal wind speed at the southern side of the pre-TC center does not increase substantially until about 12 h after TCFA. This suggests that the influence of equatorial westerly flow may not be strong in these formations. When the relationship of the formation time of these trade wind surge cases with the MJO active-westerly period is examined, low correlation is obtained and thus the role played by intraseasonal oscillation should be minimal.

On temporal variability, examination of the average zonal wind speed in the region 15°–25°N, 120°E–180° shows that the trade wind surge cycles have periods

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**Fig. 14.** (a) JMA surface weather maps at 0000 UTC 28 Nov 2004 associated with Typhoon Nanmadol (2004). H\(_{-36h}\), H\(_{-24h}\), and H\(_{-12h}\) (L\(_{-36h}\), L\(_{-24h}\), and L\(_{-12h}\)) indicate the location of the high pressure system [the pre-Nanmadol (2004) disturbance] at 36, 24, and 12 h before the current time. QuikSCAT oceanic winds are at (b) 0818 and (c) 1912 UTC 28 Nov. The TMI rain rate (shaded, unit: mm h\(^{-1}\)) at (b) 0937 UTC 28 Nov (+5 h); GOES-9 IR temperature lower than \(-32^\circ\)C (shaded, interval: 20°C) is at (c) 1900 UTC 28 Nov (+16 h).
of approximately 15–20 days during the winter months (Fig. 15), which is similar to that of the Siberia high pressure system activities. However, it can also be seen from Fig. 15 that there are episodes of trade wind surges without TC formation, and similar situation occurs in every year examined. Besides the necessary large-scale environmental conditions for TC formation (Gray 1968, 1998), the particular mesoscale features depicted in the last section may be crucial to determination of the formations.

The evolution of mesoscale features forced by trade wind surges during the formation period appears to exhibit particular patterns. For example, a convective line is located at the southern edge of the trade wind area in the early stage. This convective line mostly develops first in the northeastern quadrant of the incipient vortex, and may penetrate into the northwestern quadrant. At a later stage, other convective lines may be initialized by the increasing cyclonic circulation of the incipient vortex that converges with the trade winds to the east of the vortex center. However, usually the trade winds decrease prior to the TCFA and the formation follows the previous active mesoscale convective systems. Thus, the role of convective line associated with trade wind surges needs further exploration.

Previous studies show that multiple mesoscale convective systems formed around the incipient vortex may contribute either positively or negatively to intensification. On the negative side, the MCSs may block the low-level moisture flow into the core part of the system, deplete the convective energy and obstruct the intensification of the incipient vortex. If the MCSs are embedded in convective lines far away from the system center similar to those identified in trade wind surge TCs, the latent heat release does not warm the core region and again this is not favorable for intensification (Guinn and Schubert 1993). On the other hand, the MCSs can be the building blocks to assist the concentration of vorticity and heating as described in Montgomery et al. (2006) in the context of discussing vortical hot towers. Nevertheless, some important issues cannot be fully understood because of the low spatial and temporal data resolution. For instance, does the incipient vortex form mainly from the shear vorticity in the trade wind surges or develop in its own in the monsoon trough environment just like many other TC formations in the WNP? The examples of Typhoons Bolaven and Nanmadol show that the large vorticity patches associated with trade wind surges are several hundred kilometers away from the system center. How do these off-center vorticity patches

Fig. 15. Hovmöller diagram of the 850-hPa average zonal wind speed in the domain 15°–25°N, 120°E–180° from October to December in (a) 1993 and (b) 2004. Solid circles indicate the formation date and longitude of the trade wind surge TCs, and open circles are for the nontrade wind surge TCs.
contribute to the final axisymmetrization process for formation? There are also questions associated with the vertical development processes. Since the forcing from the trade wind surges is at lower levels and often concentrates at eastern side of the incipient vortex, how is the efficiency of midlevel vortex formation from this configuration of forcing compared with other late-season formation cases in the monsoon trough? These questions will be addressed in a follow-up study that utilizes numerical simulations on some of the illustrative formations cases in this study.

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