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Linkage Between Westerly Wind Bursts and Tropical Cyclones

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Key Points:

- The majority of WWBs were associated with TCs in the western tropical Pacific, and the 3-D structure of WWBs highly resembled that of TCs
- The TC-WWB connection explains the unidirectional nature of WWBs, the state dependency, seasonality, and spatial distribution of WWBs
- With skillful seasonal forecast of WWB-associated TCs, one may predict the seasonal activity of WWBs and thus improve El Niño prediction

Supporting Information:

- Supporting Information S1

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Abstract The westerly wind burst (WWB) in the equatorial Pacific strongly impacts on the genesis and diversity of El Niño, as manifested by its crucial role in the 2014–2016 El Niño events. However, the origin of WWB is still far from clear, rendering El Niño prediction, a persistently challenging task. Here we confirm a robust linkage between WWB and tropical cyclone (TC) from a set of observational and reanalysis data. Specifically, about 69% of WWBs were closely associated with TCs in the western tropical Pacific, and the three-dimensional structure of WWBs highly resembled that of TCs. Such a close relationship readily explains not only the unidirectional and intermittent nature of WWBs but also the state dependency, seasonality, and spatial distribution of these bursts. An important implication is that, with skillful seasonal forecast of WWB-associated TCs, we may be able to predict the seasonal activity of WWBs and thus improve El Niño prediction.

Plain Language Summary The westerly wind bursts (WWBs) frequently occur in the western-central equatorial Pacific. Previous studies have confirmed that WWBs play an important role in triggering and maintaining El Niño, including the extreme 2014–2016 El Niño events. Improving the prediction of WWBs will be no-doubt to benefit El Niño prediction, but the origin of WWB is still far from clear. Here we found that the majority of WWBs are closely associated with tropical cyclones (TCs) in the western Pacific. The existence of such a close relationship makes good sense and is easy to understand, because TCs always produce equatorial westerly winds as long as they are not too far from the equator, and because the TC movements tend to make these westerlies burst like. Aside from explaining the unidirectional and intermittent nature of WWBs, the WWB-TC linkage also explains the state dependency, seasonality, and spatial distribution of WWBs. Our results imply that one may be able to improve El Niño prediction with a skillful seasonal forecast of TCs and the consequent seasonal activity of WWBs.

1. Introduction

Frequent occurrences of westerly wind bursts (WWBs) in the western-central equatorial Pacific and the sensitivity of the equatorial ocean dynamics to this type of atmospheric perturbation have long been recognized (Lengaigne et al., 2004; McPhaden, 1999; Vecchi, 2000; Vecchi et al., 2006). By driving strong anomalous eastward surface currents and exciting downwelling equatorial Kelvin waves, WWBs can play a key role in the development of El Niño events (Fedorov et al., 2014; Lian et al., 2014; McPhaden, 2004; McPhaden et al., 1988). Recent studies further indicate that El Niño is likely a result of the interplay between a self-sustaining symmetric oscillation dictated by classic theories and WWBs that are partially modulated by El Niño itself (Chen et al., 2015; Eisenman et al., 2005). The former provides a basic dynamical framework, while the latter gives rise to different flavors of El Niño, including its irregularity, asymmetry, and extremes. In particular, strong and congregated WWBs are fundamental for extreme El Niño events to occur (Chen et al., 2015; Levine et al., 2016; Lian et al., 2016; McPhaden, 1999; Vecchi et al., 2006). It has been shown that the absence of the strong El Niño in 2014 that was expected by many, and the sudden occurrence of the super El Niño in 2015 that was not anticipated in advance, could be attributed to the lack of WWBs in the spring and summer of 2014 and their opportune appearance in the same seasons of 2015 (Chiodi & Harrison, 2017; Lian et al., 2016; McPhaden, 2015; Menkes et al., 2014).

Therefore, for improved prediction of El Niño, especially the extreme events, we need to understand where WWBs are originated from and how predictable they can be, which at present are still open questions. Previous studies have tried to relate the genesis of WWBs to the cold surges, Madden-Julian Oscillations (MJO), and convective Rossby waves (Love, 1985; Puy et al., 2015; Yu et al., 2003), but none of these

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processes can explain the majority of WWB occurrences (Chiodi et al., 2014; Feng & Lian, 2018; Oh et al., 2015), and neither can they explain why there are a great many more WWBs than easterly wind bursts (Seiki & Takayabu, 2007). Alternatively, relating WWB to tropical cyclone (TC) may provide a straightforward explanation for the unidirectional nature of these wind bursts. Considering the fact that TC centers have to be outside of the equatorial band, and thus they always produce equatorial westerlies if they are not too far from the equator (Keen, 1982), it seems quite plausible to take TCs as a primary source for WWBs (Hartten, 1996; Vecchi, 2000). However, not every TC is associated with equatorial WWBs (Vecchi, 2000), and the relationship between TC and WWB is still far from clear (Harrrison & Giese, 1991). In this study, the TC-WWB connection and the characteristics of the subset of TC that is associated with WWB are investigated. In addition, a tentative but possible way to predict this subset of TC at a few seasons in advance is provided.

2. Data and Method

The observational data used in this study include the surface wind from the Advanced Scatterometer (ASCAT) satellite data sets (Figa-Saldaña et al., 2002), the cloud cover from Multifunctional Transport Satellite data sets (Kigawa, 2001), and the TC position from the International Best Track Archive for Climate Stewardship (IBTRACS) data set. Also used is the surface wind and surface pressure (SP) from European Centre for Medium-Range Weather Forecasts daily ERA-Interim reanalysis in the period of 1979–2015 with a spatial resolution of 0.5° × 0.5° (Dee et al., 2011). The analysis domain is set to the western-central Pacific (40°S–40°N, 110°E–160°W). The anomaly is defined as the departure from the climatological seasonal cycle.

The TCs in the ERA-Interim reanalysis are identified as follows. At each grid point, if the magnitude of the negative daily SP anomaly is larger than 3 times the standard deviation, then a TC is regarded to occur on this day at this grid point and is labeled as $P(D, i)$. Here D and i denote the day and the ith TC on that day, respectively, with i spanning from 1 to $N(D)$, where $N(D)$ is the number of TC on day D. A total of 6,192 TCs are found in the ERA-Interim reanalysis over the study domain during the period of 1979–2015. The TCs identified this way generally match those from the IBTRACS data (supporting information Figure S1).

When all TCs are identified, for each $P(D, i)$, we compare the distance between $P(D, i)$ and $P\ (D + 1, j)$, where j spans from 1 to $N(D + 1)$ if applicable. This distance is the daily movement of TC. Assuming the minimum distance is identified at $P(D + 1, j)$, and this minimum distance is less than 15°, we view $P(D, i)$ and $P(D + 1, j)$ being at one TC track with the same track number. This step is repeated until all $P(D, i)$ are labeled by a track number. Here the limit of 15° is determined using the daily movement speed of TC from the IBTRACS (supporting information Figure S2). For each given track, which contains many stages of the TC, the day when the SP anomaly attains the minimum is defined as Day 0 for the TC.

A WWB event is defined, after passing a 40-day high-pass filter, as an equatorial (5°S–5°N) westerly wind gust with a zonal extent of at least 10°, a duration of at least 2 days, and a maximum wind speed anomaly exceeding the WWB selecting criterion. The default value of the WWB selecting criterion is 5 m/s. This definition is similar to those used in previous studies (Chen et al., 2015), with a focus on the intraseasonal variability (Puy et al., 2015). For each WWB, the longitude of the maximum westerly is referred to as the longitude of the WWB, and the day when the maximum westerly is found is defined as Day 0 for the WWB.

Using the identified WWBs and TCs, a WWB is considered to be associated with a TC only when the following two criteria are satisfied: (1) The SP anomalies at all grid points along the line from the center of WWB to the center of TC are negative; (2) The maximum angle between surface wind anomaly vectors at any two grid points along the line from the center of WWB to the center of TC is less than a WWB-TC associating criterion (supporting information Figure S3). In the case study shown in Figure 1, this maximum angle is 59.09°. Hence, we choose 60° as the default value for the WWB-TC associating criterion. Our sensitivity tests indicate that the results of this study are not particularly sensitive to the choice of the WWB selecting criterion within a reasonable range nor to the choice of the WWB-TC associating criterion as long as it is larger than 60° (supporting information Figures S10 and S11).

3. Results

We first present a case study of WWBs-TC connection in the western-central Pacific. Figure 1 shows a snapshot of the observed double cyclones straddling the equator along 170°E on 10 March 2015, which were

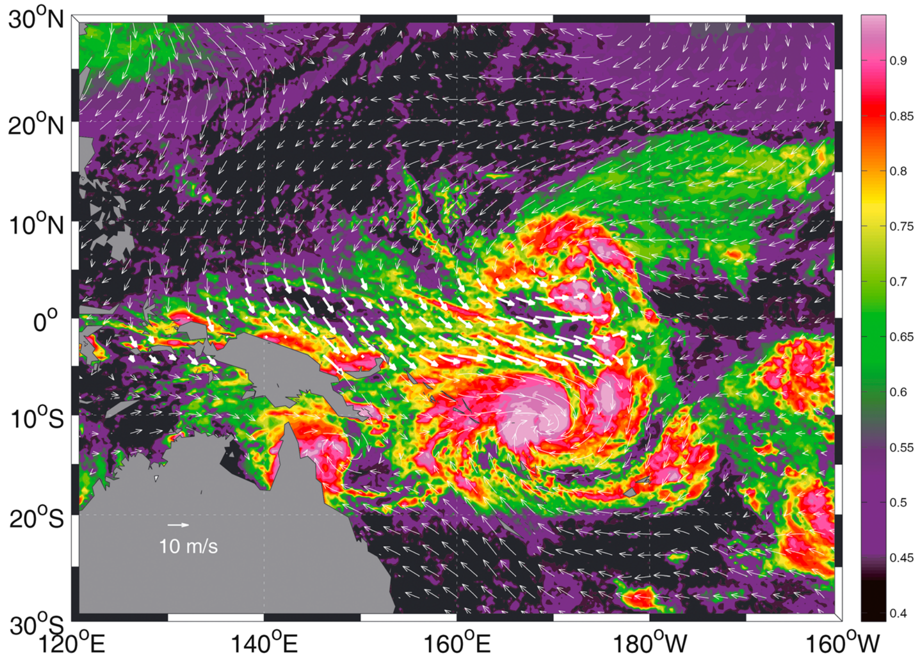

Figure 1. Satellite observed surface winds (vectors) and cloud cover (color enhanced) on 10 March 2015 in the western tropical Pacific. The wind data are from ASCAT and the cloud data from MTSAT. The westerly winds near the equator (5°S–5°N) are highlighted to show the WWB event at the time. WWB = westerly wind burst; ASCAT = Advanced Scatterometer; MTSAT = Multifunctional Transport Satellite.

apparently responsible for the equatorial WWB event that had a significant contribution to the 2015 El Niño (Chiodi & Harrison, 2017). To overcome the limitation of observational data availability, we have used the ERA-Interim reanalysis for more detailed analyses of the relationship between TCs and WWBs. Figure 2 displays the concurrent evolution of a WWB event and the associated TCs from 7 to 16 March 2015. The date when this WWB reached its maximum strength was 10 March 2015, the same as that shown in Figure 1. It is clear that the observed wind field and the position of TCs are well reproduced in the reanalysis. Three days before the WWB maximum (Day −3), there were a pair of TCs centered around 10°N and 10°S, with the one in the South Pacific being stronger, which together gave rise to the westerlies on the equator. From Day −3 to Day 3, these two TCs closely accompanied the development of the WWB. On Day 6, the TC in the Southern Hemisphere moved away from the tropics, while the one in the Northern Hemisphere went westward but remained close to the equator. Consequently, the WWB weakened and moved westward. At least for this particular event, the initiation and evolution of WWB were clearly controlled by the TCs near the equator.

We then analyzed the relationship between WWBs and TCs in a statistical sense. It is found that about 69% of the WWBs in the western equatorial Pacific were associated with the TCs in the western Pacific (Figure 3a). Specifically, 24% and 18% of the WWBs were linked to the TCs that occurred over the western North Pacific (WNP) and the western South Pacific (WSP), respectively, while 27% of the WWBs were related to the double TCs straddling the equator with one over WNP and the other over WSP, as the case shown in Figures 1 and 2. It has been suggested that WWBs could lead to the development of TCs (Love, 1985), but we found that most WWBs were associated with TCs before WWBs reaching their maxima, indicating TCs are primarily a cause rather than a result of WWBs. In accordance with the large seasonal shift of TC activities between the two hemispheres (Chu, 2004), there is a remarkable seasonality in the association of WWBs to TCs, with a higher percentage of WWBs related to the WNP TCs in boreal summer and to the WSP TCs in boreal winter (Figures 3b and 3c). Interestingly, the percentage of the WWBs that are simultaneously related to the TCs in both WNP and WSP, as well as the percentage of the total WWBs associated with TCs, are significantly higher in boreal winter, probably because TCs in boreal winter are closer to the equator than in boreal summer.

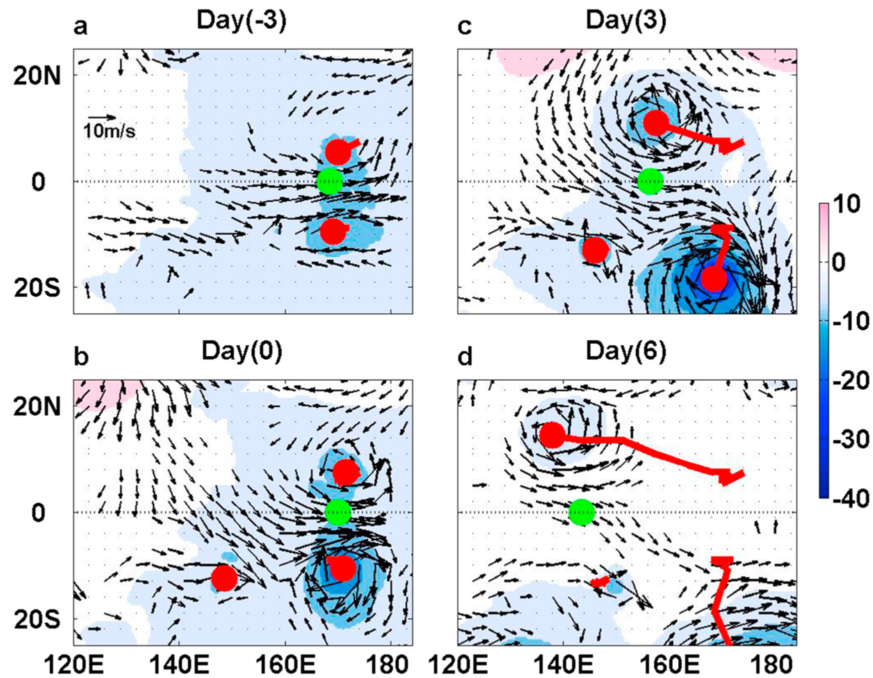

Figure 2. Concurrent evolution of a WWB event and TCs during 7–16 March 2015. Colors and vectors are for surface pressure anomaly (unit of hPa) and wind anomaly (unit of m/s), respectively. Green and red dots mark the center positions of the WWB and TCs, respectively. Thick red curves denote the TC tracks. Day (0) is the day when the WWB reached its maximum. WWB = westerly wind burst; TCs = tropical cyclones.

Another verification for the close linkage between WWB and TC is to compare their three-dimensional structures. Composites of anomalous wind fields at different pressure levels are shown in Figure 4 for WWBs associated with TCs in WNP (Figure 4a) and for all TCs in WNP (Figure 4b). Both composites have a cyclonic structure from the surface to 250 hPa, with a zonal extent of about 40° and a meridional extent of about 25°. There are strong westerlies on the equatorward side of the cyclonic motion in both cases (right on the equator for WWBs), with a maximum at the 850-hPa level (Hartten, 1996; Oh et al., 2015). There are also strong

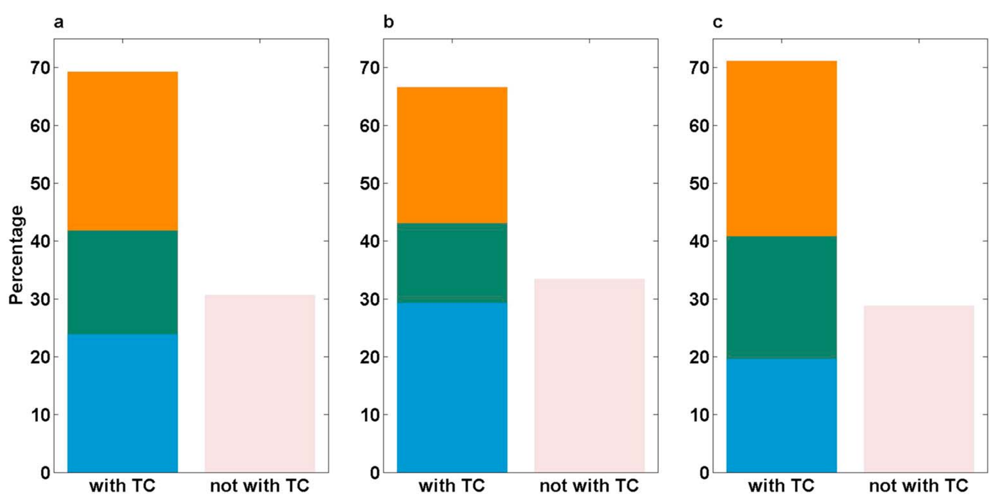

Figure 3. Percentages of WWBs associated with and not with TCs. Blue, green, and orange bars denote WWBs associated with TCs in WNP, in WSP, and in both regions. Pink bar denotes WWBs not associated with TCs. Figures 3a–3c are for the whole year, the boreal summer half (March to August), and the boreal winter half (September to February), respectively. WWBs = westerly wind bursts; TCs = tropical cyclones; WNP = western North Pacific; WSP = western South Pacific.

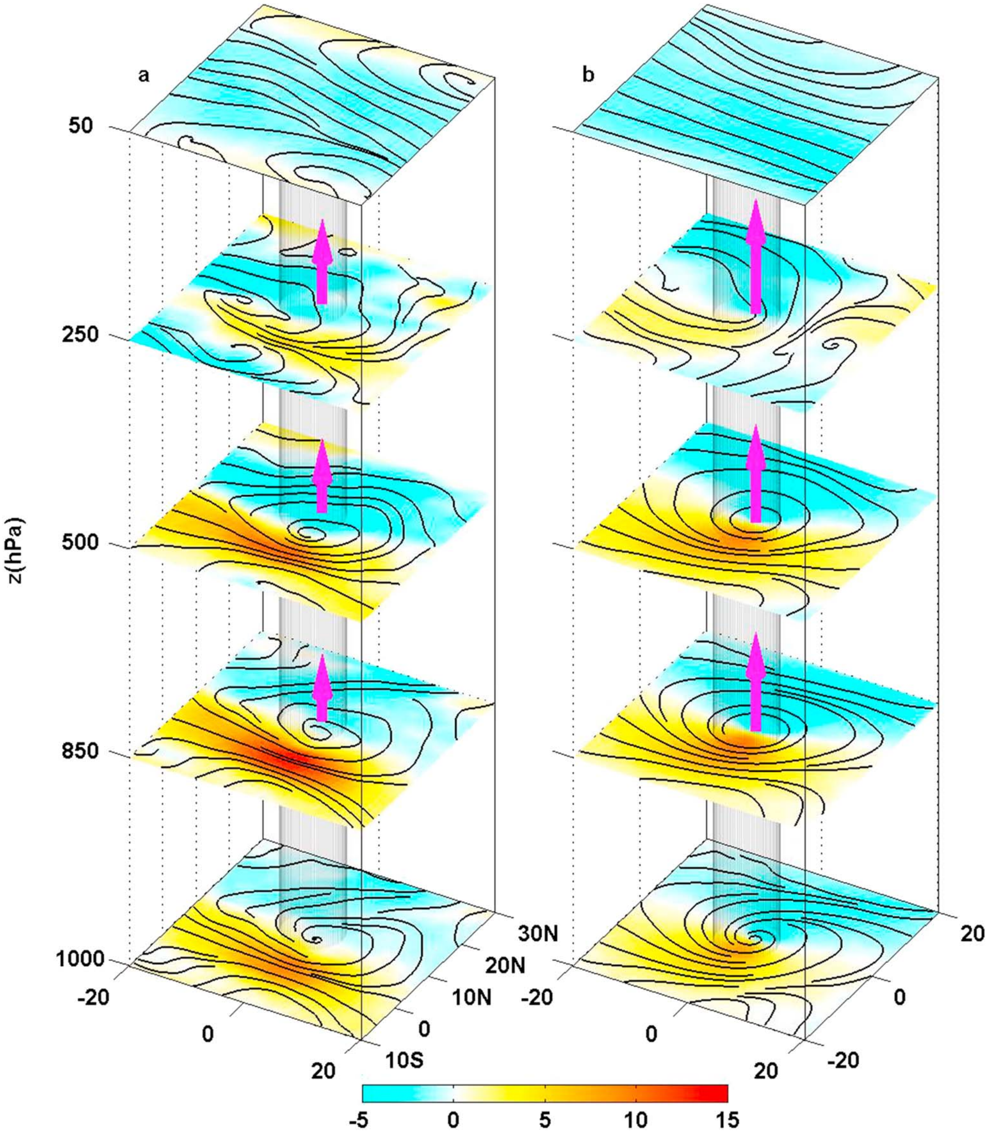

Figure 4. Composites of anomalous wind fields of WWBs (a) and TCs (b) in WNP. Colors and contours are for the zonal wind anomaly (m/s) and the stream function, respectively. Gray columns represent the center of cyclone with a radius of 5°, where the purple arrows denote the vertical velocity averaged in the column. WWBs = westerly wind bursts; TCs = tropical cyclones; WNP = western North Pacific.

convergence toward the cyclone center and associated upward motion throughout the troposphere, while at 50 hPa the prevailing wind anomalies turn to easterlies (Hartten, 1996; Oh et al., 2015). The striking similarity between the two composites suggests that WWBs are indeed a surface manifestation of the TC wind fields that reach the equator. Similar results are obtained for the WWBs associated with the TCs in WSP, and in both WNP and WSP (supporting information Figure S4).

Although the majority of WWBs are associated with TCs, not every TC can lead to a WWB (Vecchi, 2000). It is conceivable that a TC has to be either close to the equator or strong and large enough to produce a WWB. Figure 5 shows the dependence of the WWB-related TCs on their distance from the equator and on their strength as measured by the SP anomaly at the cyclone center. Indeed, the percentage of TCs that are associated with WWBs is proportional to TC strength but inversely proportional to its latitudinal position. In other words, for TCs with a certain strength, the closer to the equator, the larger influence they would have on WWBs; and for TCs at a certain latitude within the tropics, the stronger they are, the more likely they would become a source of WWBs. Note that shown in Figure 5 are the chances of TCs to be related to WWBs rather

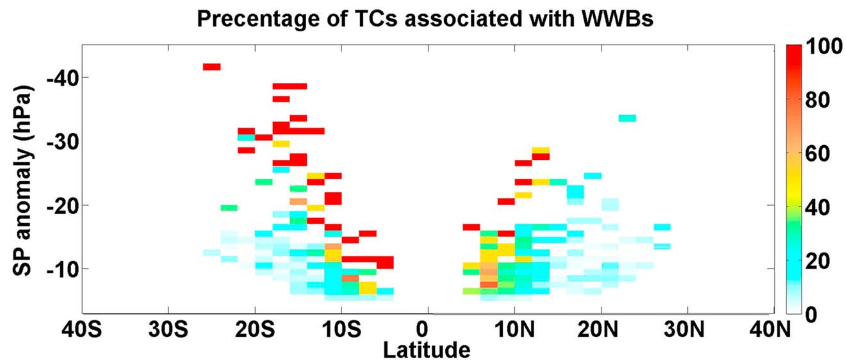

Figure 5. Distribution of the percentage of TCs associated with WWBs as a function of the latitude and the surface pressure anomaly at the TC center. WWBs = westerly wind bursts; TCs = tropical cyclones; SP = surface pressure.

than the actual numbers of TCs associated with WWBs. Because TCs are more populated toward lower latitudes and weaker strengths (supporting information Figure S5), the relatively weak TCs close to the equator are the primary driver for WWBs.

Linking WWB to TC can also provide viable interpretations for several distinct characteristics of WWBs that have not been explained previously. First of all, the TCs in the tropical WNP are more frequent and stronger and move more southeastward in El Niño years, because of the enhanced low-level shear vortices generated by the eastern equatorial Pacific warming (Wang & Chan, 2002). Such a TC variability is consistent with the fact that WWBs tend to occur more frequently and extend further to the east during the development of El Niño (Chen et al., 2015; Chiodi & Harrison, 2017; Levine et al., 2016; Lian et al., 2014; McPhaden, 1999; Vecchi, 2000), thus explaining the state dependency of WWBs. Moreover, in boreal winter, TCs are more active in WSP and are located closer to the equator in WNP (supporting information Figure S1), which explains why there are more WWBs found in boreal winter (Harrison & Vecchi, 1997). Finally, with both hemispheres considered, TCs are generally stronger, more abundant, and located closer to the equator in the western Pacific as compared to other basins (Chu, 2004), which explains why the WWBs occurring in this region are relatively frequent and strong, and thus more pronounced.

4. Discussion and Conclusions

Of particular interest is the implication of our finding to El Niño prediction. Although some previous studies suggested that the stochastic nature of WWBs could degrade the predictability of El Niño from the order of years (Chen et al., 2004) to 2–3 months (Tippett et al., 2012), the robust linkage between WWB and TC provides a more optimistic perspective. Since the occurrence of El Niño depends on the accumulative effects of WWBs over the spring and summer seasons rather than the exact timing of individual events (Chen et al., 2015; Levine et al., 2016; Lian et al., 2016), it is possible to improve El Niño prediction with skillful seasonal forecasts of TCs and thus WWBs in the western Pacific.

The state-of-the-art models have shown significant skills in predicting the seasonal activities of TCs in the western Pacific (Liu & Chan, 2012; Manganello et al., 2015; Zhang et al., 2016), including their total number, geographical distribution, and accumulated cyclone energy (ACE). In addition, we have found a high correlation between the total ACE in the western Pacific and the ACE of WWB-associated TCs (0.75 at the 99% confidence level over the past 37 years). Therefore, it is conceivable to build a dynamical-statistical hybrid model for the seasonal forecast of the WWB-associated TCs at useful lead times and to apply the results to accounting for the effects of WWBs in El Niño prediction models. For such a forecasting procedure to work, the WWB-associated TCs have to be predicted without any preknowledge of the upcoming climate state, so that WWBs do not depend on the El Niño–Southern Oscillation state that they are used to predict. A preliminary analysis shows that the winter zonal sea surface temperature (SST) gradient in the western-central tropical Pacific could be used as a predictor for the ACEs of both total and WWB-associated TCs in the following seasons (supporting information Figures S6 and S7), but more rigorous tests on this will be needed.

It is worth noting that the TC-WWB linkage explains the majority but not all WWBs, and other mechanisms such as MJO and cold surge need to be considered to fully explain the genesis and the effect of WWBs (Yu et al., 2003). Our analysis suggests that the TC-associated, westward propagating WWBs and the MJO-associated, eastward propagating WWBs have comparable characteristics in duration, strength, and zonal scale (supporting information Figure S8). In addition, the dynamical ocean responses to these two sets of WWBs, as manifested by the oceanic first-baroclinic Kelvin wave (Kessler et al., 1995; Hendon et al., 1998; Zhang & Gottschalck, 2002), are comparable in magnitude (supporting information Figure S9). Nevertheless, given the fact that TCs account for many more WWBs than MJOs do (about 69% versus 41%; Feng & Lian, 2018), the TC-associated WWBs should generally play a more crucial role in modulating El Niño. It should be emphasized that nearly 32% of WWBs were simultaneously associated with TCs and MJOs (supporting information Figure S8), indicating strong dynamical connections between TCs and MJOs in the tropical western Pacific (Liebmann et al., 1994). To fully understand the origins of WWBs, their potential predictability, and their impacts on El Niño–Southern Oscillation, we may need to take into account the interactions and collective effects of all kinds of organized atmospheric variabilities associated with WWBs.

In summary, we have confirmed a robust linkage between WWB and TC by analyzing a set of high-resolution reanalysis and observational data. About 69% of the WWBs that occurred in the equatorial Pacific during 1979–2015 were closely associated with TCs, as evidenced by their spatial and temporal concurrences, as well as their highly coherent three-dimensional structures. The existence of such a close relationship makes good sense and is easy to understand, because TCs always produce equatorial westerly winds as long as they are not too far from the equator, and because the TC movements tend to make these westerlies burst like. Aside from explaining the unidirectional and intermittent nature of WWBs, the WWB-TC linkage also explains the state dependency, seasonality, and spatial distribution of these wind bursts. More importantly, because of the crucial role of WWBs in El Niño development, our results imply that we should be able to improve El Niño prediction with a skillful seasonal forecast of TCs and the consequent seasonal activity of WWBs.

Acknowledgments
All data analyzed here are openly available. The ASCAT is from http://www.remss.com/missions/ascat, the MTSAT data are from http://weather.is.kochi-u.ac.jp/sat/ALL, the IBTRACS data are from http://www.ncdc.noaa.gov/ibtracs/index.php?name=wmo-data, and the ERA-Interim reanalysis data are from http://apps.ecmwf.int/datasets/data/interim-full-daily. This work is supported by grants from the China Ocean Mineral Resources Research and Development Association program (DY135-E2-3-01), the National Natural Science Foundation of China (41690121, 41690120, 41506025, and 41621064), and the National Program on Global Change and Air-Sea Interaction (GASI-IPOVAI-04). The authors thank two anonymous reviewers and the Editor for their thoughtful and constructive suggestions that have improved the manuscript.

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