Asymmetry of Westerly and Easterly Wind Events: Observational Evidence

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Abstract
Westerly (WWEs) and easterly (EWEs) wind events, short-lived anomalous westerly and easterly surface winds, are known to occur with unusual large magnitude over the equatorial Pacific. As the frequency of occurrence and dependence on background conditions are yet to be fully clarified, we analyzed daily surface winds for 1982–2013 from which WWEs and EWEs are detected. Both types of events appear over the Pacific warm pool, where sea surface temperature (SST) is sufficiently high for active deep convection, and favorably occur with increasing Niño4 SST. However, the frequency of occurrence of EWEs is less than that of WWEs, resulting in asymmetry in wind amplitude. Local and remote anomalous convections are equally important in exciting these events, but different local development processes cause the asymmetry in the frequency of occurrence. These results can also be seen in wind stress anomalies, albeit obscured due to nonlinearity therein.

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1. Introduction
Short-lived anomalous westerly wind epochs over the equatorial Pacific, westerly wind events (WWEs) (e.g., Luther et al. 1983; Hartten 1996; Harrison and Vecchi 1997; Seiki and Takayabu 2007a, b), act to warm the eastern equatorial Pacific (Vecchi and Harrison 2000; Lengaigne et al. 2002; Chiodi et al. 2014) and sometimes trigger El Niño (McPhaden 1999; Lengaigne et al. 2004). Eisenman et al. (2005) showed that WOE occurrence is dependent on sea surface temperature (SST) variability in the western Pacific warm pool associated with the El Niño/Southern Oscillation (ENSO) phenomenon (see also, Lengaigne et al. 2003; Vecchi et al. 2006). In contrast, anomalous easterly counterparts, easterly wind events (EWEs), induce a cold SST anomaly in the eastern Pacific and may suppress El Niño growth (Takayabu et al. 1999; Lengaigne et al. 2004; Lengaigne et al. 2006; Chiodi and Harrison 2015; Min et al. 2015). Takayabu et al. (1999) showed that an abrupt intensification of the easterly trade winds in May 1998 caused the rapid termination of 1997 El Niño. Lengaigne et al. (2004, 2006) indicated that episodic reinforcement of trade winds limits the central and eastern Pacific warming and initiates La Niña. However, very few studies have compared the statistical properties of these events and their relationship with interannual variability.

Presence of EWEs has been uncovered in two recent studies (Chiodi and Harrison 2015; Puy et al. 2015). Despite a similarity between WWEs and EWEs in terms of the spatio-temporal structure and the impact on the underlying ocean, their relationship with the interannual variability is still under debate. Chiodi and Harrison (2015) showed frequent occurrence of EWEs during the cold phase of ENSO, whereas Puy et al. (2015) argued that the above state dependence of EWEs relies on the definition and found no robust relationship between EWE occurrence and the warm pool displacement in the western Pacific once the interannual anomalies of wind stress are excluded. While Chiodi and Harrison (2015) did not make a direct comparison of the frequency of occurrence of WWEs and EWEs, Puy et al. (2015) showed that EWEs occurred as frequently as WWEs with given thresholds for the event detection. However, the use of wind stress anomaly results in an exaggeration of EWEs over the central and eastern Pacific due to nonlinearity of the wind stresses (Auxiliary Text S1 and Chiodi and Harrison 2015). This causes ambiguity in the relative occurrence frequency between WWEs and EWEs and their dependence on the background conditions, although these may influence the ENSO cycle. In this study, statistical properties of WWEs and EWEs are investigated using surface wind data, with focuses on the asymmetry of their occurrence frequencies and the relationship with the interannual SST variability.

2. Data and method
We use daily-averaged data derived from the following atmospheric and oceanic reanalysis products interpolated on a 1° by 1° grid from 1 January 1982 to 31 December 2013: the Japanese Re-Analyses 55 Years (JRA-55) data (Kobayashi et al. 2015) for atmospheric variables including the horizontal wind at 10 m height (surface wind), NOAA High Resolution SST (Reynolds et al. 2007), and interpolated outgoing longwave radiation (OLR) data provided by the NOAA/OAR/ESRL PSD (Liebmann and Smith 1998). We define anomaly as a deviation from the climatology, which is calculated as the long-term daily average for 1982–2013 with an 11-day running mean. The high-frequency (HF) component of the anomaly is then defined by subtracting the interannual component, i.e., a 91-day running mean of the anomaly, and then applying a 3-day running mean to remove daily-scale noise. The sum of the climatology and the interannual component is regarded as the background state for the HF anomalies.

Several criteria have been used to detect WWEs in surface wind datasets (Hartten 1996; Harrison and Vecchi 1997; Seiki and Takayabu 2007a; Chiodi et al. 2014). Following the previous investigations into WWEs, we extract WWEs and EWEs based on the method in Seiki and Takayabu (2007a) using the HF surface wind anomaly averaged between 2.5°S and 2.5°N. The thresholds of the magnitude, duration, and zonal extent are 5 m s−1, 2 days, and 10° in longitude, respectively. An event is required to satisfy the three thresholds at each grid over the equatorial Pacific (120°E–80°W). Note that results are qualitatively similar with different thresholds for wind magnitude (Auxiliary Table S1 and Fig. S1a). The central day and longitude of each event are determined by the date and location of the maximum magnitude of the event. An event is considered to be consecutive when its center is less than 10° in longitude distant from its position in the previous day.

In the composite analysis, the central longitude of each event is set to be 0° in relative longitude (hereafter, RL). In the eddy kinetic energy (EKE) tendency analysis, the HF anomaly of zonal wind at 850 hPa is decomposed into the eddy (u′, higher than about 20 days) and intraseasonal (u″, lower than about 20 days) components. Since barotropic energy accumulation due to the low-level zonal winds is a dominant contributor to the EKE generation at lower levels along the equator (Fig. S4), the difference in developing processes between WWEs and EWEs is demonstrated by

\[
\frac{\partial K'}{\partial t} = -u' u' \frac{\partial U_u}{\partial x} - v' u' \frac{\partial \mathbf{v}'}{\partial x} + R,
\]

where \(K' \equiv u'^2 + v'^2/2\) is the EKE, \(v'\) is the eddy component of the meridional wind at 850 hPa, the overbar indicates an 11-day
running mean, $U_0$ is the background of the zonal wind, and $\beta$ indicates the other terms. For calculating the statistical significance level, a two-tailed Student's t-test is conducted assuming that individual events are independent.

3. Results

We detected 101 and 23 WWEs and EWEs for 32 years, respectively (Fig. 1a). The number of events varies with slightly different detection thresholds, but the frequency of occurrence of EWEs is less than that of WWEs regardless of the threshold (Auxiliary Table S1). This robust asymmetry in the frequency of occurrence may cause WWEs to have stronger magnitude and longer duration than EWEs. However, both events favorably occur in a similar season and location (Fig. S5c, d); they occur rarely in the boreal summer but frequently in the boreal winter, and preferentially appear over the Eastern Hemisphere (a few WWEs are also observed over the Western Hemisphere).

The relationship between event occurrence and interannual SST variability is shown in Fig. 1. A comparison of the number of events with the time series of the monthly Niño4 SST anomaly (160°E−150°W, 5°S−5°N) shows that WWEs and EWEs are both observed frequently during the positive Niño4 SST anomaly. Indeed, the histogram of the event occurrence and the probability density function (PDF) calculated by the Epanechnikov kernel (Kimoto and Ghil 1993) indicate that both WWEs and EWEs have a very similar shape skewed toward the positive Niño4 SST anomaly. This is supported by the composite horizontal structure of the interannual component of the SST anomaly that is broadly positive to the east of the events (Fig. S6). Since the Niño4 SST anomaly is related to the warm pool expansion having important roles in El Niño onset and growth (Picaut et al. 1996; Lengaigne et al. 2007), this asymmetry in occurrence is consistent with the dependence on the background SST (Fig. S2).

The dependence of the HF zonal wind including the WWE/ EWE events on the background SST and OLR is presented in Fig. 2. The HF wind anomaly greater than $5 \text{ m s}^{-1}$ or less than $-5 \text{ m s}^{-1}$, thresholds for the WWE and EWE, preferentially occurs when the background SST is greater than 28.5°C (Fig. 2a) and when OLR is less than 230 W m$^{-2}$ (Fig. 2b). This indicates that the warm pool, where the SST is sufficiently high for active deep convection, is favorable not only for WWEs but also for EWEs, consistent with the fact that the eastward expansion of the warm pool or the positive Niño4 SST anomaly is accompanied by the frequent occurrences of WWEs and EWEs (Fig. 1).

Any difference in occurrence frequency of WWEs and EWEs is unclear when using the HF zonal wind stress anomaly. The nonlinearity of the wind stress anomaly with respect to the wind background (e.g., Trenberth et al. 1989) makes the anomaly sketched negatively (Fig. S2) and exaggerates the EWE occurrences over the central and eastern Pacific (Fig. S3), as suggested by Chiodi and Harrison (2015). This exaggeration of EWEs obscures the asymmetry in the frequency of occurrence except for extremely strong events (Auxiliary Table S1), consistent with Puy et al. (2015), and their dependence on the background (Fig. S1). See auxiliary Text S1 for further discussion.

The structure of the WWE and EWE is examined using the composite analysis. The composite horizontal structures of the WWE and EWE are shown in Fig. 3. Ensemble average OLR anomalies at the peak date are similar to each other except with the sign reversed (Fig. 3a, b). The WWE (EWE) is shown...
to couple with in situ active (suppressed) convections, which accompany anomalous convections having the opposite sign and extending in the upstream region from $-90^\circ$ to $-30^\circ$ in RL. Such horizontal structures are also seen in Fig. 4 of Puy et al. (2015), but only the in situ anomalies were focused. To show the relative importance of the remote convective activity, a dynamical analysis is conducted using a linear baroclinic model (LBM) (Watanabe and Kimoto 2000) with the composite backgrounds forced by anomalous heating that mimics the anomalous convections (see auxiliary Text S2). This demonstrates that local and remote convective activities are equally important for intensifying the zonal wind anomalies associated with the WWE and EWE (Figs. 3c and S8).

An analysis on the EKE at the peak date demonstrates the difference in development processes near the central longitude between the WWE and EWE. The EKE of the WWE is larger than that of the EWE along the equator (Fig. 4a, b). The EKE is generated due to barotropic energy accumulation by $U_u$ for both the WWE and EWE (Fig. 4c, d). On the other hand, the EKE tendencies associated with $u'$ have asymmetric structures between the WWE and EWE (Fig. 4e, f). Since the peaks of both terms for the WWE share their locations, the EKE is effectively generated, resulting in the deep westerly along the equator (Fig. S7a). This is not the case for the EWE, causing the less frequent occurrence of EWEs. That is, the asymmetry in the intraseasonal zonal wind embedded in WWEs and EWEs contributes nonlinearly to the asymmetry in the frequency of occurrence.

4. Concluding discussion

Here, we have shown observational structures of WWEs and EWEs and their relationship with the interannual SST variability in the equatorial Pacific based on reanalysis data. The analysis of HF surface wind anomalies indicates that (i) the frequency of occurrence of EWEs is less than that of WWEs regardless of the threshold for wind magnitude to detect events, (ii) background states of SST greater than 28.5°C and OLR less than 230 W m$^{-2}$, geographically corresponding to the Pacific warm pool, are favorable for development of both WWEs and EWEs, and thereby they occur more frequently with increasing Niño4 SST, and (iii) the surface wind of WWEs (EWEs) is intensified not only by the active (suppressed) convection locally but also by the broadly suppressed (active) convection at the far western side of the events.

The asymmetry in the frequency of occurrence of WWEs and EWEs is caused by the asymmetry in the local EKE generation associated with intraseasonal disturbances embedded in them. The asymmetry in the frequency of occurrence might also originate from other reasons. The PDF of convective activity is nonlinear as the suppression of deep convection is bounded by clear skies (Zhang 1993). The easterly associated with suppressed convection might be weaker than the westerly associated with the active deep convection. However, well-suppressed convective anomalies are rarely related to the detectable WWEs in our analysis; therefore, it is insufficient to explain the asymmetry only by the nonlinearity in deep convection. There is also a possibility that interaction with the ocean brings asymmetry between WWEs and EWEs (Lengaigne et al. 2003; Eisenman et al. 2005; Vecchit et al. 2006). While WWEs may act to shrink the warm pool and result in unfavorable condition for subsequent EWEs, WWEs tend to result in subsequent WWEs by expanding the warm pool (e.g., Lengaigne et al. 2002, 2003, 2004; Miyama and Hasegawa 2014) since both events preferentially occur over the warm pool and the positive Niño4 SST anomaly. Further study is needed to estimate the impact of this coupled process on the asymmetry.

The remote suppressed (active) convective anomaly of the WWE (EWE) may be associated with the Madden-Julian oscillation (cf. Zhang 2005) because of their eastward propagation from $-90^\circ$ to $0^\circ$ in RL with a phase speed of about 5 m s$^{-1}$ and baroclinic structure (Fig. S10). On the other hand, the cyclonic and convective signal prior to the WWE, propagating eastward slowly from $-50^\circ$ to $0^\circ$ in RL and having a baroclinic structure (Figs. S10a and S11a), is not robust as mentioned in previous studies (Seiki and Takayabu 2007a; Chiodi et al. 2014), implying the importance of local development processes for WWEs. The westward propagation of cyclonic vorticity lagging the WWE (Fig. S9a) is probably related to a single cyclone or a series of cyclones in one or both hemisphere (Harrten 1996; Harrison and Vecchi 1997). A westward-propagating disturbance with anticyclonic vorticity, leading the EWE (Fig. S9b) and having the equivalent barotropic structure (Fig. S10b), could be convectively coupled equatorial Rossby waves (Kiladis and Wheeler 1995; Yang et al. 2007; Puy et al. 2015). This accompanies a negative specific humidity anomaly in the mid-troposphere and subsidence through the troposphere (Figs. S10b and S11b), contributing to suppress the convection associated with the EWE.

The difference in the frequency of occurrence and the similarity in the dependence on background states are important aspects of WWEs and EWEs. For instance, more frequent occurrence of WWEs than EWEs with the similar state dependence may contribute to net warming at the equatorial Pacific probabilistically. The impact of state-dependent stochastic forcing on ENSO asymmetry was shown in a conceptual model (Jin et al. 2007); therefore, our observational analysis indicating probabilistic state dependence of both WWEs and EWEs suggests that the relationship between WWEs/EWEs and interannual SST variability in the central equatorial Pacific can be partly responsible for the irregular behavior of ENSO (Chen et al. 2015).

Fig. 4. Horizontal structures of the composite of (a, b) the EKE with colors $[m^2 s^{-2}]$ and its tendencies due to the zonal gradients of the (c, d) background and (e, f) intraseasonal zonal winds at 850 hPa with colors and contours $[10^{-7} m^2 s^{-4}]$ for (left) WWEs and (right) EWEs at the peak date. Vectors indicate the 3-day running means of the (a, b) eddy, (c, d) background, and (e, f) intraseasonal components of the horizontal winds at 850 hPa $[m s^{-1}]$. Gray shade in (c–f) indicates the value does not exceed 95% statistical confidence.
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Supplements

Supplementary material 1 provides discussion of the use of the surface wind or wind stress data to detect WVEs and EWEs (Text S1), model experiments to estimate the efficiency of the convective anomalies (Text S2), additional figures (Figs. S1 to S11) and a table (Table S1) for supporting the main text.

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