Assessing the Relationship between MJO and Equatorial Pacific WWBs in Observations and CMIP5 Models

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(Manuscript received 5 August 2017, in final form 6 May 2018)

ABSTRACT

This study evaluates the relationship between the Madden–Julian oscillation (MJO) and the occurrence of equatorial Pacific westerly wind bursts (WWBs). During the convective MJO phase, anomalous surface westerlies prevail in and west of the convective MJO center, providing favorable conditions for WWBs. Compared with the probability of WWBs expected under a null hypothesis that WWBs occur randomly, the convective MJO phase almost doubles the probability of a WWB occurring. Nevertheless, only 34.46% of WWBs co-occur with the convective MJO, which is much less than that reported in previous studies. We show that when the MJO and WWBs are defined using the same field with overlapping frequencies, the percentage of WWBs co-occurring with the convective MJO shows a significant increase. However, the higher percentage is simply caused by the fact that the strong WWBs during a convective MJO are more likely to be identified than those during the suppressed and neutral MJO phases. A total of 45.80% of WWBs are found to occur in the full MJO phase (both the convective and suppressed MJO phases), which is slightly higher than that expected based on randomness. Although the full MJO has statistically significant impact on the likelihood of WWBs, the influence from the full MJO on the tropical Pacific sea surface temperature anomaly is much weaker as compared to that from the WWBs. The relationships between the MJO and WWBs simulated in CMIP5 models are also assessed, and the percentage of WWBs that co-occur with the MJO simulated in models is in general less than that in observations.

1. Introduction

Westerly wind bursts (WWBs), characterized by a lifetime of 2–30 days, a zonal fetch of 1000–3000 km, and maximum anomalous wind speeds exceeding 5 m s^{-1} , are unique events that occur in the western-central equatorial Pacific (Harrison and Vecchi 1997). By forcing strong and warm eastward advection near the equatorial date line, and downwelling Kelvin waves along the equatorial waveguide, WWBs play a crucial role in triggering, maintaining, and modulating El Niño (McPhaden et al. 1988; McPhaden 1999, 2004; Vecchi and Harrison 2000; Lian et al. 2014; Chen et al. 2015). Previous studies reported that WWBs can be associated with tropical cyclones, cold surges, and the Madden–Julian oscillation (MJO) (e.g., Keen 1982; Love 1985; Hartten 1996; Lin and Johnson 1996). However, whether the MJO significantly influences the occurrence of the majority of the WWBs remains uncertain.

During the convective MJO phase, anomalous surface westerlies tend to prevail in and west of the convective MJO center (Madden and Julian 1972), providing favorable conditions for WWBs to occur. For example, Lin and Johnson (1996) showed that two WWBs, which occurred during the intensive observing period (IOP) of the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean–Atmosphere Response Experiment (COARE), were preceded by convective MJO phases. Yu and Rienecker (1998) pointed out that the strong and congregated WWBs that occurred in 1997 were associated with a series of MJOs. Oh et al. (2015) reported that three MJOs were observed during the Dynamics of the Madden–Julian Oscillation (DYNAMO) field campaign from late 2011 to early 2012, and each event was accompanied by one or more WWBs.

Statistical relationships between MJO and the occurrence of WWBs was also presented, but with contradictory conclusions. Seiki and Takayabu (2007) showed that the patterns in anomalies of surface wind and convection associated with WWBs are similar to those

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DOI: 10.1175/JCLI-D-17-0526.1

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associated with the convective MJO phase, and suggested that more than 90% of WWBs are associated with the MJO. Puy et al. (2016) found that nearly all strong WWBs co-occurred with a convective MJO, and concluded that about 57% of the WWBs occur in the convective MJO phase. Conversely, Chiodi et al. (2014) pointed out that the evolution in sea surface temperature (SST) anomalies along the equatorial Pacific waveguide is different following MJOs with and without WWBs. In addition, the likelihood of finding an accompanying WWB in the western-central equatorial Pacific during the MJO does not significantly differ from that expected under the null hypothesis that WWBs occur randomly.

Fasullo and Webster (2000) suggested that while sustained WWBs (i.e., lifetime greater than 25 days) are associated with a convective MJO phase, brief WWBs (lifetime less than 25 days) occur independently of the MJO. Puy et al. (2016) claimed that the disparity between the results of Seiki and Takayabu (2007) and Chiodi et al. (2014) was caused by the different methodologies used to define the MJO in the two studies. It is clear that the different conclusions as to the relationship between convective MJO phase and WWBs may be dependent on the definitions of the MJO and WWBs.

Since WWBs are characterized by a sudden increase in westerlies from the sea surface to the midtroposphere over the western-central equatorial Pacific (Hartten 1996), fields such as the wind velocity at 10 m, 1000 hPa, or 850 hPa or surface zonal wind stress are used for their detection (e.g., Murakami and Sumathipala 1989; Hartten 1996; Harrison and Vecchi 1997; Menkes et al. 2014). Generally, WWBs behave as irregularly repeating atmospheric perturbations (Gebbie and Tziperman 2009) and are therefore defined by the surface westerly anomaly or the surface zonal wind stress anomaly when compared with the climatology (e.g., Harrison and Vecchi 1997; Menkes et al. 2014; Lian et al. 2014). However, as WWBs exhibit a form of intraseasonal variability, WWBs have also been defined by the band-passed surface westerly or surface zonal wind stress (e.g., Fasullo and Webster 2000; Seiki and Takayabu 2007).

To define the MJO, Wheeler and Kiladis (1999) identified the MJO from the wavenumber-frequency spectrum of the symmetric part of the outgoing longwave radiation (OLR). The MJO signals over specific regions can be captured well using this method. Puy et al. (2016) detected the MJO in a similar manner but using the band-passed signal of surface zonal wind stress. Fasullo and Webster (2000) defined the MJO as the band-passed signal of OLR. On the other hand, since the MJO involves strong intraseasonal air-sea interactions, using a single field may not capture the detailed

evolution of the MJO. The index of Wheeler and Hendon (2004) considers the evolution of OLR and zonal winds at 850 and 200 hPa over the tropics, and realistically captures the MJO signal on a global scale. However, local-scale MJO signals over specific regions may not be accurately depicted by this single index. Given such broad methods for defining both WWBs and the MJO, it is necessary to test the relationship between the MJO and WWBs using different criteria. It will be shown in section 3 that the percentage of WWBs that occurred in the convective MJO phase varies considerably when different definitions for WWBs and the MJO are used.

If the MJO can largely increase the likelihood of WWBs occurring, as suggested by Seiki and Takayabu (2007) and Puy et al. (2016), improvements in simulating the MJO in models will in turn improve the simulation of WWBs, and subsequently El Niño. Therefore, it is worth assessing the relationship between the MJO and WWBs occurring in state-of-the-art models. Seiki et al. (2011) examined the relationship between the MJO and WWBs simulated in 18 models participating in phase 3 of the Coupled Model Intercomparison Project (CMIP3) and found that the WWBs are closely related to the simulated MJO in the majority of the models. Considerable progress in representing the MJO in models has been made following CMIP3 (Hannah and Maloney 2011; Kim et al. 2011, 2012; Subramanian et al. 2011; Zhou et al. 2012; Wolding et al. 2016; Ahn et al. 2017). Hung et al. (2013) concluded that the models participating in CMIP5 (Taylor et al. 2012) show improvement over those from CMIP3 in reproducing the spectral peak and variance of the MJO. Lian et al. (2017) examined the relationship between WWBs and MJO in only a single CMIP5 model, but found that the influence of the MJO on WWBs is weaker than that in observations. However, an examination of the relationships between the MJO and WWBs occurring in a large ensemble of CMIP5 models has not yet been undertaken.

This study aims to reconcile the relationship between the MJO and WWBs by using multiple detection methods for defining the MJO and WWBs. The relationship between the MJO and WWBs occurring in 23 CMIP5 models is also examined. The rest of this paper is arranged as follows: Section 2 describes the data and methods. In section 3, we examine the relationship between WWBs occurring and the convective MJO in the observations, and the sensitivity of the results to different WWB and MJO definitions. Section 4 provides the results from the CMIP5 models. In section 5, we discuss the relationship between WWBs and the full MJO (both the convective and suppressed MJOs) in observations, and the implications of our findings for clarifying the

TABLE 1. Description of the field data and data-processing methods used to identify WWBs. References with similar field data and data-processing methods are listed.

Label	Descriptions	References
W1	The u_{10} anomaly defined as the departure from daily climatology.	Chiodi et al. (2014)
W2	The τ_{10} anomaly defined as the departure from daily climatology.	McGregor et al. (2015)
W3	The 2–30-day band-passed u_{10} .	Fasullo and Webster (2000)
W4	The 2–90-day band-passed u_{10} .	Seiki and Takayabu (2007)
W5	The 2–90-day band-passed τ_{10} .	Puy et al. (2016)

different influence of MJO and WWBs on El Niño development, followed by concluding remarks in section 6.

2. Data and methods

a. Data

We used daily surface winds at 10 m and 850 hPa and zonal winds at 200 hPa from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim). Daily OLR from the National Oceanic and Atmospheric Administration (NOAA) and the weekly SST from the NOAA Optimum Interpolation SST (OISST) version 2 (Reynolds et al. 2002) were also used. The period of observations was 1979–2013, at a spatial resolution of $2.5^\circ \times 2.5^\circ$. The model simulations were the first ensemble member (r1i1p1) from 23 CMIP5 models (listed in Table 5) forced with historical greenhouse gas concentrations (Taylor et al. 2012), covering the period 1980–2005. Model outputs were interpolated onto the same resolution as the observations. Anomalies were defined as the departure from the daily mean climatology.

b. Definition of WWBs

In this study, a WWB is defined according to the following criteria: 1) the zonal wind anomaly at 10 m (u_{10} anomaly) averaged between 2.5°S and 2.5°N exceeds a given threshold, 2) the zonal extent of the area satisfying criterion 1 should be at least 10° in longitude, and 3) the first two conditions should persist for at least 2 days. The domain of interest is the equatorial Pacific (2.5°S – 2.5°N , 120°E – 100°W). Here, the threshold used in criterion 1 is 5.5 m s^{-1} , equals to 3 times the standard deviation of the u_{10} anomaly averaged globally over the equatorial band. This definition of WWBs is labeled as W1 in Table 1.

Four other different definitions of WWBs (referred to as W2–W5; Table 1), each using different field or data-processing methods, were also used. In W2, the field used in W1 is replaced by the surface zonal wind stress τ_{10} converted from u_{10} (Harrison and Chiodi 2009) given $\tau_{10} = \rho_a C_d |\mathbf{U}_{10}| u_{10}$. Here, ρ_a is the density of air (1.25 kg m^{-3}), C_d is the drag coefficient (1.3×10^{-3}), and $\mathbf{U}_{10}$ is the wind vector at 10 m. In W3 and W4, the

second-order Butterworth filter was applied to u_{10} to obtain the 2–30- and 2–90-day band-passed fields. In W5, a 2–90-day bandpass filter is applied to τ_{10} . For each definition, the threshold is the 3 times standard deviation of the resulting field averaged globally over the equatorial band. For example, the threshold used in W3 is 3 times standard deviation of 2–30-day band-passed u_{10} averaged globally over the equatorial band. Noted that the field data and data-processing methods used in these definitions have been used in other studies (Table 1).

For each WWB, the central location and day were calculated as follows (Puy et al. 2016):

$$\text{lon0} = \frac{\iint \text{lon}(x) u_{10}(x, t)}{\iint u_{10}(x, t)} \quad \text{and} \quad (1)$$

$$\text{day0} = \frac{\iint \text{time}(t) u_{10}(x, t)}{\iint u_{10}(x, t)}, \quad (2)$$

where the integral is computed over the spatiotemporal domain of the field associated with a given WWB. The strength of a WWB was defined as the integral of the field associated with the WWB.

Figure 1 compares the WWBs identified in 1997 using the five different definitions of WWBs. The strong WWBs concentrated west of the 28.5°C isotherm, as observed in 1997 (McPhaden 1999), are clearly identified by the five methods. The WWBs identified by the W1 and W2 methods are relatively long-lasting with a large zonal extent. In addition, some WWBs identified by the W4 and W5 methods are located east of the 28.5°C isotherm. The annual occurrence of WWBs identified by the five methods varies from 5.1 to 8.2 per year (Fig. 2a), close to that proposed in previous studies (Seiki and Takayabu 2007; Chiodi et al. 2014).

c. Definition of the MJO

Table 2 lists the four different methods used to define the MJO in this study (referred to as M1–M4). The first method (M1) is the same as that of Wheeler and Kiladis

FIG. 1. WWBs (circles) that occurred in 1997 in the observations as identified by the (a) W1, (b) W2, (c) W3, (d) W4, and (e) W5 definitions. Color shading denotes the field anomaly. The field anomaly is u_{10} (m s^{-1}) for (a), (c), and (d) and zonal wind stress (N m^{-2}) for (b) and (e). Black lines indicate the 28.5°C isotherm.

(1999), who defined the MJO as the symmetric part of the globally averaged OLR between 15°S and 15°N , with wavenumbers 1–5 and periods of 30–90 days in the wavenumber–frequency domain. The second method (M2) is similar to M1, except that OLR is replaced with surface zonal wind stress, following Puy et al. (2016). The third method (M3) is based on the empirical orthogonal function (EOF) of the combined fields of globally averaged OLR, and zonal wind at 850 and 200 hPa, between 15°S and 15°N (Wheeler and Hendon 2004). Once the leading pair of principal components is obtained, which characterized the evolution of the MJO, the OLR field for a given time is reconstructed from the summation of the two EOFs multiplied by their respective principal components, similar to Wheeler and

Hendon (2004). The fourth method (M4) is that of Fasullo and Webster (2000), in which an MJO index is defined from the 30–90-day band-passed globally averaged OLR between 15°S and 15°N .

For each method, the resultant field was normalized by its standard deviation between 130°E and 160°W (Puy et al. 2016). During the convective (suppressed) MJO phases, anomalous surface westerlies (easterlies) prevail in and west of the convective (suppressed) MJO center. Therefore, in M1, M3, and M4, convective and suppressed MJO phases are defined as the region in the time–longitude diagram with a normalized band-passed OLR anomaly less than -1 and greater than 1 , respectively. In M2, the convective and suppressed MJO phases are defined as the region in the time–longitude

FIG. 2. (a) Annual occurrence of WWBs as identified by the five WWB definitions (b) Annual occurrence of the MJO as identified by the four MJO definitions.

TABLE 2. Description of the field data and data-processing methods used to identify the MJO.

Label	Descriptions	References
M1	Global-averaged OLR between 15°S and 15°N with the wavenumbers 1–5 and periods of 30–90 days.	Wheeler and Kiladis (1999)
M2	Global-averaged τ_{10} between 15°S and 15°N with the wavenumbers 1–5 and periods of 30–90 days.	Puy et al. (2016)
M3	Empirical orthogonal function of the combined fields of global-averaged OLR and 850- and 200-hPa zonal winds between 15°S and 15°N.	Wheeler and Hendon (2004)
M4	The 30–90-day band-passed global-averaged OLR between 15°S and 15°N.	Fasullo and Webster (2000)

diagram with a normalized surface wind stress greater than 1 and less than -1 , respectively. Above definitions of WWBs and the MJO were applied to both the observations and models, unless otherwise stated.

Figure 3 presents the composites of the 30–90-day band-passed OLR and 30–90-day band-passed surface zonal wind during the convective and suppressed MJO phases. Here, the MJO was identified using M1. The composites are constructed from the dates and longitudes when maximum negative and positive 30–90-day band-passed OLRs occurred. In addition, only those results that are significantly different from zero (at the 95% confidence level using the one-sample Student's t test) are shown. It is evident that westerly (easterly) anomalies prevail in regions of strong convection (suppression), driving an anomalous large-scale surface zonal wind background that favors (hinders) the occurrence of WWBs. Seiki and Takayabu (2007) showed that the WWBs are coincident with deep convection over the equator. Therefore, the convective MJO is more likely to have the potential to increase the likelihood of WWBs occurring than the suppressed MJO, as illustrated by some previous studies (e.g., Fasullo and Webster 2000). As the main focus of the current study is

to assess whether the MJO increase the likelihood of WWBs occurring as compared with that expected from the randomly distributed WWBs, only the relationship between the convective MJO phase and WWBs occurring is discussed in the following analyses in sections 3 and 4. The overall influence of the full MJO (both the convective and suppressed phases) on the occurrence of WWBs is discussed in section 5.

Figure 4 compares the evolution of the convective MJOs identified in 1997 using the four MJO definitions. All four MJO identification methods capture the series of the convective MJOs that were observed in the western-central Pacific in 1997 (McPhaden and Yu 1999). However, differences are found in the zonal extent, propagation speed, and frequency of the convective MJO identified by the different methods. The annual frequency of the convective MJO is shown in Fig. 2b, where the average annual occurrence of the convective MJO is 5.23.

d. Monte Carlo bootstrap test

The Monte Carlo bootstrap test was used to examine whether the percentage of WWBs co-occurring with the MJO is significantly different from that expected from

FIG. 3. Composite of the 30–90-day band-passed OLR anomaly (color shading; W m^{-2}) and 30–90-day band-passed surface wind anomaly (vectors) in the (a) convective and (b) suppressed MJO phases. Only the composites significantly different from zero (at the 95% confidence level) are shown.

FIG. 4. Convective MJOs in 1997, as identified by the (a) M1, (b) M2, (c) M3, and (d) M4 definitions.

randomly distributed WWBs. The MJOs are fixed in the time–longitude diagram, and the central day of each WWB was randomly shifted by ± 45 days, which is the observed average recurrence time between two consecutive WWBs. However, the results were insensitive to the number of days used as the center day dithers (not shown). For each time, the percentage of randomly distributed WWBs embedded within the MJOs was calculated. The process was repeated 10 000 times, and the probability distribution function of the percentage was estimated. If the percentage of the observed WWBs embedded in the MJO was located toward the narrow tail of the distribution (e.g., p value > 0.95), then it was considered statistically significant; otherwise, the change in occurrence of WWBs was deemed insignificant.

3. Results from observations

a. Relationship between convective MJO and the occurrence of WWBs

The relationship is first assessed using the definitions of W1 and M1 for WWBs and the MJO, respectively. Figure 5 presents the time–longitude evolution of MJOs and WWBs in 1997. Four of the nine WWBs that occurred in 1997, including the strong WWBs that occurred between mid-March and mid-May, are embedded in a convective MJO phase. Figure 6 shows the composite of the convective MJO phase centered on the day and the

longitude of the maximum negative band-passed OLR, with the WWBs overlain on these data. Note that some WWBs embedded in the convective phase of a specific MJO are now located out of the region where the composite band-passed OLR is negative. Although WWBs tend to cluster along the convective MJO phase, the majority of WWBs, including a number of strong WWBs, occur in the absence of convective MJO. Overall, 35.31% of the identified WWBs are embedded in the convective MJO phases. From the Monte Carlo bootstrap simulation, the 5% and 95% likelihoods of randomly distributed WWBs are 15.03% and 22.38%, respectively, with a median of 18.53%. It is clear that, although the convective MJO phase almost doubles the likelihood of WWBs occurring, the MJO is not the major source in driving WWBs.

The percentage of the time–longitude domain used to define the convective MJO phase in the time–longitude domain (i.e., 1979–2013, 120°E – 100°W) is 9.49%. This percentage is less than the median of the 5% and 95% likelihoods of randomly distributed WWBs (i.e., 18.53%), simply because most of the WWBs occurred in the equatorial western and central Pacific.

Strengthening the criterion for identifying strong WWBs from 3 to 4 times the standard deviation increases the percentage of WWBs embedded in the convective MJO to 46.49%, more than double the likelihood expected from randomly distributed WWBs

FIG. 5. Time-longitude diagram of the convective MJOs (color shading) and WWBs (dots) in 1997. Black dots denote WWBs embedded in the convective MJO phase. Red dots denote WWBs in the absence of the convective MJO phase. The size of each dot is proportional to the strength of the WWB.

(i.e., a median percentage of 21.55%). This suggests that the MJO tends to increase the likelihood of strong WWBs, consistent with the findings of Seiki and Takayabu (2007) and Puy et al. (2016).

b. Sensitivity of the results

Table 3 presents the percentage of WWBs embedded in convective MJO using combinations of the different definitions for the MJO and WWBs. All of the percentages are greater than the 95% likelihood of randomly distributed WWBs, indicating that the significant increase in the likelihood of WWBs occurring during convective MJO is robust, irrespective of the definitions of WWBs and the MJO. However, the percent of WWBs co-occurring with the convective MJO shows a wide variation. Higher percentages can be found when the frequency used for defining WWBs overlaps the frequency of the MJO. For example, the frequency of the MJO is explicitly fixed at 30–90 days using M1 (Table 2). When the WWBs are defined by W5, in which a 2–90-day bandpass filter is applied to τ_{10} (Table 1), 42.26%

FIG. 6. Composite of the convective MJO phase, overlain with WWBs. The convective MJO is identified according to M1, and WWBs are identified according to W1. The composite is centered on the maximum negative band-passed OLR anomaly. Color shading and dots are as in Fig. 5.

of the WWBs are found in the convective MJO. This percentage is greater than that when the WWBs are defined by W1, in which the frequency for WWBs is not predetermined.

High percentages of WWBs embedded in the convective MJO phase can also result from using the same field to define both WWBs and the MJO. For example, the combination of M2 and W2 uses τ_{10} to define WWBs and the MJO. Here, the percentage of WWBs embedded in convective MJO increases to 44.07%, greater than when WWBs are defined using u_{10} (W1; Table 1). The largest percentage is obtained when the MJO and WWBs are both defined using the same field in addition to overlapping frequencies (i.e., the combination of M2 and W5). This combination results in 56.49% of WWBs being associated with convective MJO, which is consistent with the results of Puy et al. (2016).

Gebbie and Tziperman (2009) pointed out that the recurrence times between two consecutive WWBs are irregular. Lian et al. (2017) showed that the lifespan of WWBs ranges from 5 days to more than 60 days. Therefore, owing to the sporadic nature of WWBs, the high-frequency bands used (e.g., those in W3–W5) are not expected to completely identify all the WWBs that occur. A simple idealized experiment is used here to highlight how filtering alters the characters of WWBs considerably, together with their relationship with the MJO.

In the idealized experiment, a total of 317 WWBs are randomly distributed throughout a 40-yr time series, where the annual occurrence of the WWBs is comparable to that in the observations (Fig. 2). Two additional oscillations are imposed on the time series: an MJO-like signal with a period of 50 days (Zhang 2005) and an El Niño–Southern Oscillation (ENSO)-like signal with a period of 4 years (Philander 1990). The magnitudes of the u_{10} anomalies assigned to the MJO, WWBs, and

TABLE 3. Percentage of WWBs embedded in the convective MJO. Numbers in parentheses are the median of the 5% and 95% likelihoods (%) of WWBs occurring, as expected under the null hypothesis of randomly scattered WWBs using Monte Carlo bootstrap simulations.

		Method used to define MJO			
		M1	M2	M3	M4
Method used to define WWBs	W1	35.31 (18.53)	38.11 (15.73)	31.54 (15.77)	32.87 (15.34)
	W2	40.00 (19.63)	44.07 (16.30)	33.59 (16.12)	36.04 (14.08)
	W3	34.87 (16.01)	33.15 (14.61)	32.54 (15.38)	31.64 (13.10)
	W4	45.00 (17.14)	51.43 (15.51)	40.26 (16.15)	44.94 (14.45)
	W5	42.26 (17.15)	56.49 (17.15)	37.67 (16.25)	42.95 (15.81)

ENSO are 1.0, 6.0, and 1.5 m s^{-1} , respectively. These magnitudes are estimated from the composite of u_{10} anomalies associated with the convective MJO phase, WWBs, and ENSO. Here, the MJO is represented by u_{10} anomalies, meaning that positive and negative values represent convective and suppressed MJO phases, respectively. El Niño years are defined as those years for which the u_{10} anomaly is greater than one standard deviation from the mean. In addition, WWBs occur more frequently during El Niño years compared with the neutral and La Niña years (Harrison and Vecchi 1997); therefore, the frequencies of WWBs for El Niño years and all other years (i.e., both neutral and La Niña years) are set to 12.7 and 5.5 per year, respectively. In general, the MJOs occur more frequently and are stronger in

magnitude during the El Niño years compared with the La Niña years (Lau and Chan 1988). However, as the main focus here is on whether the MJO influences the occurrence of WWBs, for simplicity the effect of ENSO on the MJO is not examined in the idealized experiment.

Figure 7a presents the evolution of the raw time series from the idealized experiment; only the first four years are shown for clarity. Figures 7b–d show the evolution of the time series after 2–90-day, 2–30-day, and deseasonalization processing has been applied to the raw time series. The 2–90-day bandpass filter causes the magnitude of the WWBs to decrease considerably (Fig. 7b). In addition, many fewer WWBs were identified in the absence of a convective MJO phase (second row in Table 4). Consequently, the relationship between the

FIG. 7. (a) Results of an idealized experiment undertaken to identify WWBs in a time series, and using a (b) 2–90- and (c) 2–30-day bandpass filter, and (d) removing the climatological daily mean. Vertical lines in (a) denote WWBs. Black horizontal lines in (b)–(d) denote 3 times the standard deviation as the threshold for identifying WWBs. Only the results from the first four years are shown for clarity.

TABLE 4. Percentage of WWBs identified by the three data-processing methods used in the idealized experiment.

Method	Total	Convective phase	Suppressed phase	Neutral phase
2–90-day bandpass filter	49.53	99.65	7.69	47.27
2–30-day bandpass filter	96.21	95.95	98.72	95.15
Deseasonalization	86.75	99.65	73.08	87.88

convective MJO phase and the occurrence of WWBs appears to be strong. When WWBs are identified in the 2–30-day band-passed and deseasonalized time series, the majority of the randomly distributed WWBs are successfully identified (third and fourth rows in Table 4). However, the magnitude of the identified WWBs is also reduced using the 2–30-day bandpass filter (Fig. 7c). Considering that WWBs are nonregularly repeating events and there are other surface wind variations that occur with frequencies of 2–30 days (Wheeler and Kiladis 1999), the deseasonalization procedure is deemed more appropriate to identify the WWBs than any high-pass or bandpass filter. The results from the idealized experiment suggest that the stronger relationship between the MJO and WWBs, as derived using W3–W5 to define WWBs, is a product of the method used.

A distinct feature of WWBs is the strong westerly anomalies along the equator. By definition, τ_{10} increases nonlinearly with an increase in u_{10} . Strong WWBs identified by the W1 method can thus be identified by the W2 method. However, since the meridional component also plays a role in determining τ_{10} , an event with weak u_{10} anomalies and strong meridional surface wind anomalies could be identified as a WWB event using the W2 method. For example, Fig. 8 shows the equatorially averaged u_{10} anomalies, meridional surface wind anomalies, and τ_{10} anomalies associated with a WWB from 13 to 15 January 1982 as identified by W2 definition. The central location of the WWB is 165°W. The anomalous westerlies around the central location are approximately 50% weaker than the meridional component. Therefore, the WWB identified by

the W2 method in this case is characterized more by the strong anomalous surface northerlies than by westerly anomalies. In fact, 30.37% of the events identified by W2 as WWBs exhibit weak (5.5 m s^{-1} , the threshold used in W1) u_{10} anomalies. By convention, a WWB event is characterized by strong westerly anomalies (i.e., the event shown in Fig. 8 is more a northerly wind burst); therefore, the W2 method can also be deemed unsuitable to define WWBs accurately. Overall, the W1 method is considered the best choice in defining WWBs. Using the W1 method, the percentage of WWBs that occur with convective MJO ranges from 31.51% to 38.11% (second row in Table 3), with an average of 34.46%.

4. Results from CMIP5 models

a. WWBs and MJO simulated in models

Based on the results from the observations discussed in section 3b, the W1 method is used to identify WWBs in the models. In addition, the M1 method is used to evaluate the representation of the MJO in the models. The sensitivity of the model results to the definition of the MJO is discussed in section 4c.

Figure 9 presents the u_{10} anomaly averaged between 2.5°S and 2.5°N during the first half of the strongest El Niño year identified in the observations and in each model. Here, the El Niño events in the CMIP5 models are defined as events when SST anomalies averaged over the central–eastern equatorial Pacific (5°S–5°N, 150°E–90°W) were greater than half the standard deviation of the mean for more than five months

FIG. 8. The u_{10} anomalies (red) and meridional surface wind anomalies (blue) averaged at the equator during a WWB from 13 to 15 Jan 1982 as identified by the W2 definition. Orange shading denotes the zonal extent of this WWB.

FIG. 9. Time-longitude evolution of u_{10} anomalies (color shading; m s^{-1}) averaged between 2.5°S and 2.5°N in the first half of the strongest El Niño year in observations and individual CMIP5 models. In the observations, the El Niño year is 1997. Black circles denote WWBs. The sizes of the circles are proportional to the strengths of the WWBs. Green lines denote the 28.5°C isotherm.

TABLE 5. Threshold for WWB identification, and the number of WWBs and MJOs per year. The methods used to define WWBs and the MJO are W1 and M1, respectively. (Expansions of acronyms are available online at <http://www.ametsoc.org/Pubs/AcronymList>.)

Model/ observations	Threshold (m s^{-1})	WWBs per year	MJOs per year
ACCESS1.0	4.21	5.88	7.02
ACCESS1.3	4.17	6.69	7.12
CanESM2	4.40	4.35	7.65
CMCC-CESM	5.79	6.88	5.29
CMCC-CM	5.45	8.27	5.82
CMCC-CMS	6.49	11.08	4.69
CNRM-CM5	5.76	8.54	5.98
GFDL CM3	4.52	7.50	6.00
GFDL-ESM2G	4.35	4.84	7.42
GFDL-ESM2M	5.57	5.56	4.50
HadGEM2-AO	4.18	5.54	7.31
HadGEM2-CC	4.34	6.68	6.65
HadGEM2-ES	4.30	7.00	7.73
INM-CM4.0	3.56	3.65	6.40
IPSL-CM5B-LR	4.65	8.62	6.48
IPSL-CM5A-LR	3.49	5.42	6.45
IPSL-CM5A-MR	3.64	5.88	6.69
MIROC5	4.94	5.96	5.27
MPI-ESM-LR	5.91	9.88	6.31
MPI-ESM-MR	5.96	7.38	6.37
MPI-ESM-P	5.84	8.50	6.60
MRI-CGCM3	4.99	10.31	6.12
MRI-ESM1	5.01	10.88	5.98
Multimodel mean	4.85	7.19	6.34
Observations	5.50	8.17	5.60

(Bellenger et al. 2014). In the observations, the strongest El Niño year was 1997. In the models, the WWB-like signals are found in the western-central equatorial Pacific. Similar to observations, the locations of WWBs in models such as MPI-ESM-P and MRI-ESM1 show a significant eastward shift with a developing El Niño, whereas the locations of WWBs in other models such as HadGEM2-ES and IPSL-CM5A-LR do not show such a shift. Models such as ACCESS1.0, HadGEM2-ES, INM-CM4.0, IPSL-CM5A-MR, MPI-ESM-LR, MPI-ESM-MR, MPI-ESM-P, MPI-CGCM3, and MRI-ESM1 also simulate WWBs over regions where the SST is less than the 28.5°C threshold (Yu et al. 2003).

The 3 times standard deviation values and the annual occurrence of WWBs simulated in the models are listed in Table 5 (first and second columns, respectively), showing some variations among the models. The multimodel mean of the annual occurrences of WWBs is 7.19, close to that in the observations. Models such as CanESM2, GFDL-ESM2G, and INM-CM4.0 underestimate the annual occurrence of WWBs, and models such as CMCC-CMS, MRI-CGCM3, and

MRI-ESM1 simulate a larger number of WWBs than observed.

Figure 10 compares the wavenumber–frequency spectrum of the symmetric part of OLR in the observations and CMIP5 models. Similar to the observations, high energy is found in the wavenumber–frequency domain defining the MJO (i.e., zonal wavenumbers of 1–5 and periods of 30–90 days) in the majority of CMIP5 models. Several models (e.g., ACCESS1.0, CanESM2, and INM-CM4.0) also exhibit high energy in the low-frequency band with large positive wavenumbers, and the majority of the models lack high spectrum energy around the dispersion curves, indicative of equatorial Kelvin waves. Hung et al. (2013) showed that most CMIP5 models do indeed simulate Kelvin waves, based on an analysis of precipitation data. This suggests that the precipitation and cloud cover simulated in CMIP5 models is not as closely coupled as in the observations. The annual occurrence of modeled MJOs is listed in Table 5 (last column), showing that the majority of the models have an annual occurrence of MJOs comparable to the observations (i.e., 5.60 per year).

b. Relationship between convective MJO and WWBs occurring

The percentage of WWBs embedded in the convective MJO phase of each model is shown in Fig. 11. Of the 23 models, 17 show that the percentage of WWBs associated with the convective MJO phase exceeds that expected from randomly distributed WWBs. The percentages from the remaining models (i.e., CanESM2, GFDL-ESM2M, HadGEM2-AO, INM-CM4.0, IPSL-CM5A-LR, and IPSL-CM5A-MR) lie within the 5% and 95% ranges of the randomly distributed WWBs. The multimodel mean shows that 26.78% of WWBs are found in the convective MJO phase, which is less than that in observations.

The degree to which the MJO influences the occurrence of WWBs in the models is strongly dependent on how well the MJO is simulated. In the frequency band of 30–90 days, the spectrum energy of the symmetric part of OLR in the observations is largely concentrated in the region defining the MJO (i.e., wavenumbers of 1–5 and periods of 30–90 days) (Fig. 10). Figure 12 shows the relationship between the percentage of WWBs embedded in convective MJO phases and the percentage of the spectrum energy associated with the MJO in the observations and each model. Here, the percentage of the spectrum energy associated with the MJO is defined as the ratio between the spectrum energy within the region defining the MJO to that defining the total eastward-propagating intraseasonal spectrum energy (i.e., wavenumbers 1–15 and periods of 30–90 days) in the

FIG. 10. Wavenumber–frequency spectrum of the symmetric part of the globally averaged OLR between 15°S and 15°N in observations and individual CMIP5 models (color shading). Superimposed are the dispersion curves of the even meridional mode-numbered equatorial waves for the three equivalent depths of 12, 25, and 50 m. Black rectangles denote the region of the wavenumber–frequency domain used for filtering the MJO.

FIG. 11. Percentage of WWBs embedded in the convective MJO phase in CMIP5 models. The whiskers denote the 5% and 95% likelihoods of randomly distributed WWBs, with the median indicated by the black dot.

wavenumber–frequency domain. It is evident that models with more energy concentrated in the wavenumber–frequency domain defining the MJO simulate a larger percentage of WWBs embedded in convective MJO phases.

To better understand why models with more energy concentrated in the wavenumber–frequency domain defining the MJO simulate a stronger relationship with WWBs occurring, Fig. 13 compares the composites of the intraseasonal OLR and 850-hPa winds from two different models. The first model is CMCC-CMS, which shows more concentrated energy in the wavenumber–frequency domain defining the MJO. The second model is CanESM2, which shows less concentrated energy in this domain. Following Wheeler and Hendon (2004), the MJO is decomposed into eight phases, and only days when the MJO index exceeds 1.0 are used to construct the composites. It is clear that the CMCC-CMS model exhibits more organized OLR and zonal wind anomalies than CanESM2. As the WWBs were defined as any strong westerly with a zonal extent greater than 10° in longitude and lasting for at least 2 days, the westerly anomalies that prevail in and west of the well-organized convective MJO signal provide a background favorable for the occurrence of WWBs.

c. Sensitivity of model results to definition of MJO

Figure 14 shows the percentage of WWBs embedded in the convective MJO phase using the four different definitions of the MJO. Overall, large percentages result from the M2 method, and the percentage of WWBs occurring embedded in the convective MJO are larger than the 95% likelihoods of randomly distributed WWBs for all the models. The multimodel mean percentage estimated by the M2 method is 33.34%. For the M3 and M4 methods, the multimodel mean percentages are 23.11% and 23.72%, respectively. For each MJO definition, the multimodel mean percentage of WWBs associated with convective MJO is less than in the observations. This suggests that on average, the CMIP5

models underestimate the influence of the MJO on the occurrence of WWBs.

5. Discussion

a. Relationship between WWBs and the full MJO in observations

As shown in some previous studies (e.g., Fasullo and Webster 2000), the suppressed phase of the MJO significantly decreases the likelihood of WWBs occurring. From the dynamical point of view, as is evident in Fig. 4b, easterly anomalies and strong suppression that prevail in and west of the suppressed MJO center

FIG. 12. Scatterplot of the percentage of WWBs embedded in the convective MJO phase as a function of the percentage of spectrum energy associated with the MJO in observations and models. See text for details. Green dots and circles denote the results from the 23 CMIP5 models. Red and blue dots represent the observations and multimodel mean, respectively.

FIG. 13. Composite of anomalies in the intraseasonal OLR (color shading; W m^{-2}) and wind at 850 hPa (vectors; m s^{-1}) for (a) CMCC-CMS and (b) CanESM2. The number of days falling within each MJO phase is shown at the bottom right of each panel.

provide a background that hinders the occurrence of WWBs. For example, using the combination of the W1 and M1 methods to define WWBs and the MJO, respectively, only 10.49% of the observed WWBs are embedded in the suppressed MJO phase in observations. The 5% and 95% likelihoods of randomly distributed WWBs are 16.78% and 24.48%, respectively, with a

median of 20.63%. Therefore, a suppressed MJO phase significantly decreases the likelihood of WWBs occurring by approximately 50%. This conclusion is insensitive to the definition of the MJO.

It is interesting to explore whether the convective MJO phase modulates WWBs timing, and whether convective MJO causes WWBs to occur. Dynamically,

FIG. 14. Percentage of WWBs embedded in the convective MJO phase, as identified by the M1 (blue), M2 (purple), M3 (yellow), and M4 (green) methods in CMIP5 models. Filled circles indicate that the percentage falls outside the 95% likelihood of randomly distributed WWBs.

FIG. 15. Composite of anomalous SST change following (left) full MJO, (center) full MJO without WWBs, and (right) full MJO with WWBs. Contour interval is 0.2°C .

the large-scale surface westerly anomalies and deep convection associated with the convective MJO phase provide a background favoring the occurrence of WWBs. Therefore, events with surface westerly anomalies associated with the convective MJO phase are more likely to be categorized as WWBs. A similar occurrence of convective and suppressed MJO phases is seen in the observations (i.e., 193 convective phases and 196 suppressed phases using the M1 method). However, the percentage of WWBs embedded in the convective MJO phase is 3 times greater than that for the suppressed MJO phase. Furthermore, the percentage of WWBs embedded in the convective phase is significantly different from that associated with randomly distributed WWBs. These findings suggest that the convective MJO causes, rather than modulates, the WWBs. Since only the convective MJO phase significantly increase the likelihood of WWBs occurring as compared with randomness, a better prediction of the convective MJO in the equatorial Pacific will benefit the prediction of a part of WWBs occurring.

It is also of interest to assess whether the likelihood of WWBs occurring change significantly in the full MJO (both the convective and suppressed MJO phases). Using the combination of the W1 and M1 methods for defining WWBs and the MJO, respectively, the percentage of WWBs associated with the MJO (convective and suppressed phases) is 45.80%. The 5% and 95% likelihoods of randomly distributed WWBs associated with the MJO are 34.97% and 43.36%, respectively, with a median of 39.16%. Therefore, the full MJO significantly increases the likelihood of WWBs occurring, although is only a few percent more than that expected

based on randomness. Again, this result is insensitive to the definition of the MJO.

b. Influence of MJO and WWBs on El Niño development

Although the full MJO has substantial impact on WWBs likelihood, the influence from the full MJO on the tropical Pacific SST anomaly is much weaker as compared to that from the WWBs. Shown in Fig. 15 is the composite of anomalous SST change following the full MJO, full MJO without WWBs, and full MJO with WWBs. Following Chiodi et al. (2014), the composite is made regarding the full MJO occurred in ENSO-neutral conditions ($|\text{Niño-3}| < 0.75^{\circ}\text{C}$), and the changes in anomalous SST are shown at +20, +40, +60, and +80 days relative to the center day. Only the composites significant from zero are shown (at the 95% confidence level based on the Monte Carlo bootstrap test). There are 134 full MJOs in the region, of which 53 co-occurred with WWBs and 81 did not. As shown in Chiodi et al. (2014), the full MJO does not significantly increase SST anomaly in the central-eastern equatorial Pacific (Fig. 15, left). An El Niño-like pattern is found only during the MJOs that co-occurred with WWBs (Fig. 15, right). Therefore, the full MJO does not significantly influence the development of El Niño, despite of its significant impact on WWBs occurring.

Two possible reasons may explain why the full MJO has less influence on the development of El Niño. First, the surface wind anomalies during the convective and suppressed MJO are comparable in magnitude but opposite in sign (Fig. 3), so that the easterly surface anomalies during the suppressed MJO may compensate the warm anomaly induced by the westerly surface

FIG. 16. As in Fig. 15, but for convective MJOs.

anomaly during the convective MJO in a full MJO cycle. Second, as shown in the current study, the majority of WWBs occur independently of MJO. It is now widely accepted in the ENSO community that the congregated WWBs are more likely to generate a strong El Niño. For example, [Levine et al. \(2016\)](#) showed that increasing WWBs occurring could induce more extreme El Niño events. [Chiodi and Harrison \(2017\)](#) showed that when the congregated WWBs occurred in the later 2015 were added to the wind stress field in 2014, the SST anomaly in the equatorial eastern Pacific sharply increased at the end of 2014. [Figure 16](#) presents the anomalous SST changes following the convective MJO, convective MJO without WWBs, and convective MJO with WWBs. Even when the influence of the suppressed MJO is not considered, there is not significant SST warming in the central-eastern equatorial Pacific following the convective MJO ([Fig. 16](#), left). On the other hand, an El Niño-like pattern is found when MJO co-occurred with WWBs ([Fig. 15](#), right, and [Fig. 16](#), left). These results clearly suggest that the percentage of WWBs co-occurring with the convective MJO is too low to induce an El Niño-like pattern, and improving the MJO prediction does not help to improve the ENSO prediction.

6. Concluding remarks

By applying different definitions of the MJO and WWBs, this study examined the relationship between the MJO and the occurrence of the equatorial Pacific WWBs in the observations and 23 CMIP5 models. By defining WWBs using u_{10} anomalies relative to the seasonal cycle, the percentage of WWBs associated with the convective MJO phase from the observations ranges from 31.51% to 38.11%, with an average of 34.46%. The

percentages of WWBs associated with the convective MJO phase are significantly different from those expected under the null hypothesis of randomly scattered WWBs. The majority of the CMIP5 models also simulate a significant influence of the convective MJO phase on the occurrence of WWBs. The multimodel mean shows that 26.74% of WWBs are embedded in the convective MJO phase, which is less than that from the observations. As WWBs are characterized by strong surface westerly anomalies and well-organized deep convection, the degree to which the MJO influences the occurrence of WWBs in the models is dependent on how well the MJO is simulated. For example, models with a better simulation of the MJO exhibit a stronger influence of the MJO on the WWBs occurring.

The percentage of WWBs associated with the convective MJO phase was shown to be sensitive to the definition of WWBs. A higher percentage of WWBs was obtained when the MJO and WWBs were identified using the same field, or if the frequency band of WWBs overlapped that of the MJO. This bias was amplified when both these conditions were satisfied, and approximately 57% of WWBs were embedded in the convective MJO phase. These large percentages were found to be due to events that occurred in the absence of a convective MJO phase are unlikely to be identified as WWBs. Notably that while τ_{10} is the salient variable in measuring the effects of WWBs on equatorial Pacific SST, it is not an appropriate variable in defining the WWBs, simply because that some WWBs defined by τ_{10} were in fact characterized more by strong surface meridional wind anomalies than by the westerly anomalies. However, this does not deny the usability of τ_{10} from the oceanic perspective. Overall, we conclude that while the convective MJO (and the full MJO) significantly

increases the likelihood of WWBs occurring, it is not the major source in driving the WWBs. The origin of WWBs remains unresolved.

Acknowledgments. This work is supported by grants from the Scientific Research Fund of the Second Institute of Oceanography, SOA (QNYC201501), and the National Natural Science Foundation of China (41506025, 41690121, and 41690120). ERA-Interim data were obtained online at <http://apps.ecmwf.int/datasets>. The OLR data can be found online at https://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html. OISST version 2 is available online at <https://www.esrl.noaa.gov/psd/>. Model simulations are available online at <https://esgf-node.lnl.gov/search/cmip5>. We thank two anonymous reviewers for their helpful comments and suggestions.

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