Subseasonal atmospheric variability and El Niño waveguide warming; observed effects of the Madden-Julian Oscillation and Westerly Wind Events.

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Abstract

Westerly Wind Events (”WWEs”) have previously been shown to initiate and maintain equatorial Pacific waveguide warming. The relationship between WWE and intra-seasonal Oscillation (or Madden-Julian Oscillation; "MJO") activity, and the role of MJO events in initiating and maintaining equatorial Pacific waveguide warming is reconsidered here, over the time period 1986-2010. WWEs are identified in the observed record of near surface zonal winds based on an objective scheme. MJO events are defined using a widely used index, and 62 are identified over this period that occur when the El Niño-Southern Oscillation (ENSO) is in its neutral-state (|NIÑO3| < 0.75°C). 42 of these MJO events have one or more embedded WWEs and 20 have not.

We examine the time evolution of sea surface temperature anomaly over the Pacific equatorial waveguide following the westerly surface wind phase of the MJO over the western equatorial Pacific. We find that there is waveguide warming for the MJO+WWE events in similar magnitudes and amounts as following WWEs that are not embedded in an MJO, and that there is very little statistically significant waveguide warming following the MJO events that do not contain an embedded WWE. Further, we find that the occurrence of an MJO event does not significantly affect the likelihood that a WWE will occur. These results extend and confirm the results of Vecchi (2000) with a near doubling of the period of study. We suggest that understanding the sources and predictability of tropical Pacific Westerly Wind Events remains essential to improving predictions of the onset of El Niño events.

1. Introduction

Westerly Wind Events (WWEs) are zonal wind anomaly events in the western and central equatorial Pacific (Luther *et al.* 1983, Harrison and Giese 1991, Hartten 1996, Harrison and Vecchi 1997) with typical time, zonal-spatial and zonal-wind anomaly scales of 6 days, 6-7 ms^{-1} (up to 15ms^{-1} peak), and 1400-2500 km, respectively (Harrison and Vecchi 1997), that have been observed to occur during a wide range of atmospheric phenomena, including, tropical cyclones (both single and paired), cold-surges from the cold-hemisphere and convective activity associated with the Madden-Julian Oscillation, or 'MJO' (*e.g.,* Keen 1982, Harrison 1984, Love 1985 a,b; Hartten 1996; Chen et al., 1996; Lin and Johnson, 1996). WWEs with substantial wind anomaly in the western and central Pacific waveguide region (within a few degrees of the equator) have previously been shown to precede substantial (up to 1°C) equatorial Pacific cold tongue warming (Vecchi and Harrison 2000, Harrison and Chiodi, 2009) when the El Niño-Southern Oscillation (ENSO) is in neutral conditions, and maintain warm central/eastern Pacific sea surface temperature anomalies (SSTAs) in warm-ENSO conditions (Vecchi and Harrison 2000). WWEs are rare in cool-ENSO conditions, in which case their effects are difficult to determine reliably (Vecchi and Harrison 2000).

Composite single WWE wind anomalies applied to ocean general circulation models (OGCMS) have been found to produce cold tongue warming on the order of 0.5°C (Giese and Harrison 1990, 1991; Vecchi 2000; Lengaigne et al. 2002; Harrison and Chiodi 2009). There is general agreement that WWE-induced upper ocean advection anomalies are the primary cause of WWE-driven cold tongue warming. Zonal advection of the background zonal SST gradient has typically been found to be play a dominant role (Schopf and Harrison 1983; Harrison and Schopf 1984; Kindle and Phoebus 1995; Giese and Harrison 1991), although some studies have also found different types of oceanic advection anomalies, including those associated with tropical instability wave modulation of meridional advection (Giese and Harrison 1991) and subsurface advection anomalies (Richardson et al. 1999; Belamari et al. 2003) to be of central importance.

The full role of WWEs in waveguide SST changes has been found to involve coupled ocean-atmosphere dynamical processes, with WWE-driven equatorial Pacific waveguide warming acting to enhance the probability of WWEs (Perigoud and Cassou 2000; Lengaigne *et al.* 2003; Lengaigne *et al.* 2004; Vecchi *et al.* 2006; Gebbie *et al.* 2007). Thus, the influence of WWEs on ENSO is enhanced by their dependence on the state of the tropical Pacific: WWEs are not best thought of as additive noise to the state of the tropical Pacific (*e.g.,* Lengaigne *et al.* 2004; Vecchi *et al.* 2006; Eisenman et al. 2005; Gebbie et al. 2007; Gebbie and Tziperman, 2009.a,.b). Applied with frequency and number consistent with recently observed El Niño years, (multiple) WWEs have been shown to drive El Niño-like SSTAs (e.g. sustained seasonal ENSO index magnitudes of about 2°C) in realistic ocean circulation models (Harrison and Chiodi 2009).

MJO events are characterized by wind (among other) anomalies that propagate eastward at roughly 5 m s^{-1}, oscillate in the 30-90 day period range, have zonal scales typical of low-atmospheric wavenumber phenomena, and include significant (~1.5 m s^{-1} average), easterly and westerly surface wind anomalies over the equatorial Pacific waveguide (Madden and Julian, 1972). Some have previously hypothesized that MJO events are important to the development of El Niño events because of their possible connection to WWEs (e.g. Slingo et al. 1999; Seiki et al. 2007), while others have taken the view that surface wind stress variability characteristic of the MJO itself is important to the initiation and maintenance of El Niño-type tropical Pacific SSTAs.

For example, based on OGCM and coupled ocean-atmosphere model results, Kessler and Kleeman (2000) have proposed that MJO-like wind stresses in the western and central equatorial Pacific drive SSTA patterns in the western (cooling of about -0.4°C) and eastern (warming of about +0.1°C) equatorial Pacific that are conducive to the development of an El Niño event. Kessler (2001) found evidence that an extension of MJO-driven surface wind anomalies over the open waters of the western and central equatorial Pacific occurs during El Niño years, which was postulated to enhance the proposed rectification process. Seiki et al. (2009) have also postulated that changes associated with the development of El Niño events cause the MJO-associated surface winds to contribute further to El Niño-development. Alternatively, a perspective has developed over the last decade that argues that the MJO contains a "low frequency tail" (Zavala-Garay *et al*., 2003), that is correlated with interannual anomalies of MJO variability (Zavala-Garay *et al*. 2005, 2008), and is important to the development of eastern equatorial Pacific (e.g. NIÑO3 region) SSTA anomalies (Kapur *et al.* 2011; see also Zhang and Gottshalck 2002). Within this body of literature, it has been claimed that the effects of MJO wind stress anomalies in tropical Pacific SSTA variability dominate those caused by WWEs because "those wind bursts associated with the MJO are of most importance for interaction with the ocean ENSO, as a large oceanic response is only driven by wind events that are spatially and temporally coherent" (Hendon *et al.* 2007).

Which is it? Do WWEs or MJO events help initiate El Niño events? And what is the relationship between WWEs and the MJO; does the state of the MJO influence the probability of seeing a WWE? To answer these questions we analyze the historical records of subseasonal wind and SST anomaly in the 1986-2010 period, identifying the times with WWEs and MJO events, and examining the changes in equatorial Pacific SSTA that follow them. The relative numbers of

WWEs that occur during and not during MJO-events, as well as the numbers of MJO events that do and do not contain a WWE are also analyzed in the context of a bootstrap-Monte Carlo simulation to determine whether there are statistically significant relationships between the timings of these two classes of subseasonal wind events.

Our main focus is on SSTA-changes following events that occur in ENSO-neutral conditions [here defined as in Vecchi and Harrison (2000) as |NIÑO3| < 0.75°C], since we are interested, inherently and for forecasting purposes, in the processes capable of initiating or at least influencing a transition to the warm-ENSO state. The results of our study are organized as follows. Composites of equatorial Pacific SSTA-changes following MJO and WWEs are examined in sections 3 and 4. Results from companion ocean general circulation model (OGCM) experiments, in which the model-ocean is forced with representative WWE and MJO wind stress anomalies, are compared in section 5. Results from a Monte Carlo-bootstrap examination of the MJO and WWE co-occurrence statistics are examined in section 6, and a discussion and conclusions are offered in section 7.

2. Data and Methods

For information on SST variability, we use NOAA Optimum Interpolation SST (OISST) V2 provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. OISST data is available on a 1x1 degree grid at weekly resolution. For this study, this data is interpolated to daily resolution to estimate the changes in SSTA that occur over various subseasonal timescales (as described below). SST anomalies are determined using the climatological monthly mean values (base period 1986-2010), linearly interpolated to daily resolution. The same 25 year base period is used to determine climatological means (and thereby anomalies) throughout this study.

We use wind data from the 12-hourly, 2.5 by 2.5 degree ECMWF operational forecast 10-m data set (as done in Chiodi and Harrison, 2009), which is available online at http://www.ecmwf.int/products/data (provided at handling costs for research purposes).

The state of the MJO is determined using the now commonly referred to index suggested by Wheeler and Hendon (2004; WH04, hereafter), which is based on a pair of empirical orthogonal functions of the combined fields of near-equatorially averaged 850-hPa zonal wind, 200-hPa zonal wind and satellite-based outgoing longwave radiation data, is available at daily resolution from http://www.cawcr.gov.au/staff/mwheeler/maproom/RMM/. By convention, the MJO is considered active when the index amplitude is > 1 and inactive when not. We identify "MJO-events" from this daily index as those intervals in the 1986-2010 period for which the MJO-amplitude is > 1 for at least 20 consecutive days. Wind anomaly composites during these "MJO-active" times are shown in Appendix A for each of the 8 phases specified by the index, and reveal that statistically significant wind anomalies are seen over the tropical Pacific in each case. We chose to use the 20-consecutive-day requirement since it seemed prudent to focus our consideration on MJO events that reach some basic level of maturity relative to the timescale (~30-90 day) commonly understood to characterize the MJO. Trial showed that this requirement can be omitted without significantly affecting the wind anomaly composite results discussed here. Other results, such as the total number of identified MJO events, are obviously influenced at least somewhat by this requirement, but the conclusions reached regarding the relationship between the MJO, WWEs and tropical Pacific waveguide warming are not dependent on it.

We also report on a second set of results, which, rather than using the WH04 index, instead identify MJO events according to the more traditional Maloney and Hartmann (1998) methods. In this case, a separate MJO index is constructed from the principal components of the first and second empirical orthogonal functions (PC1, PC2) of 20-80-day band-passed-filtered 850-mb zonal wind, averaged from 5°S to 5°N around the equator. This index is (with "t" time in pentads);

$$\text{Index}(t) = \text{PC1}(t) + [\text{PC2}(t+2) + \text{PC2}(t+3)]/2.$$

According to this methodology, MJO events are defined as periods in which > 1 standard deviation index-peaks are found to be both preceded and followed by index-troughs. The MJO phases (1-9 in this case) are assigned as follows; phase 5 occurs during the index-peak, whereas phases 1 and 9 are the preceding and subsequent troughs. Phases 3 and 7 are the increasing and decreasing zero-crossings, respectively, and the even-numbered phases are assigned such that they are evenly spaced between the odd-numbered phases. Thus, by definition in this case, each identified MJO event includes phases 1-9, with the latter phases (i.e. 7, 8, 9) being associated with surface westerlies over the western and central Pacific. Unless noted otherwise, however, the results presented below are based on the primary WH04-based MJO-event definition.

The WWE identification and compositing method used here was developed by Harrison and Vecchi (1997) and used previously by Vecchi and Harrison (2000) and Harrison and Chiodi (2009). This method defines WWE events based on three equatorial (5°S to 5°N) regions, with boundaries at 130°E-155°E, 155°E-180° and 180°-150°W, for the so-called W-, C- and E-type WWEs, respectively. WWEs are defined as any interval of 3 or more consecutive days for which the respective WWE-region average zonal wind anomaly exceeds 2 $m \cdot s^{-1}$. Event composites are based on the identification of a center-day (Day 0), defined as the event-day with the maximum zonal wind anomaly (see Harrison and Chiodi, 2009 for more details). For reference, W-, C-, and E-type WWE composite wind anomalies for all events identified during the 1986-2010 period are shown in Appendix A.

To examine the effects of the MJO and WWEs on SSTA, we have compiled a data set consisting of the observed SSTA changes following each type of event in the 1986-2010 period. For WWEs, changes in SSTA are determined relative to the conditions seen 20 days prior to WWE Day 0. For consistency, changes following MJOs are determined 20 days prior to the first day that a given MJO event, as defined above using the WH04 index, reaches phase 6 (7 when based on the Maloney and Hartmann definition), the phase at which surface westerlies begin to dominate the MJO-composite wind anomalies in the tropical Pacific (see Appendix Figure A1). In each case, changes in SSTA at various time lags (e.g. +20, 40, 60 and 80 days) are composited over the events identified to occur in ENSO-neutral conditions. ENSO-neutral conditions are defined herein following Harrison and Chiodi (2009) and Vecchi and Harrison (2000), as the times in which the NIÑO3 index (SSTA averaged over the 150°W-90°W, 5°S-5°N region) has amplitude less than 0.75°C (i.e. $|\text{NIÑO3}| < 0.75$°C).

The statistical significances of the composite SSTA-changes are determined using a Monte-Carlo bootstrap procedure, in which random selection (with replacement) from the 1986-2010 record of all possible ENSO-neutral SSTA changes is used to estimate the probability that the magnitude of a given composite SSTA-change can be explained by the effects of random selection. The Monte-Carlo procedure is explained more in Appendix B.

The ocean model used herein is based on the longstanding NOAA primitive equation OGCM (e.g. Philander and Siegel, 1985). The configuration used here, based on NOAA's Geophysical Fluid Dynamics Laboratory Modular (GFDL) Ocean Model (version MOM4; Griffies *et al.* 2003). The global version of MOM4 is the oceanic component of the GFDL Coupled Model 2 (Gnandesikan et al. 2006), and a tropical Pacific version of the model has been used recently to successfully describe the seasonal cycle of the near surface tropical Pacific by Harrison et al. (2009) and to study the effects of WWE wind stress anomalies by Harrison and Chiodi (2009). To force the experiments described herein, wind data are converted to zonal psuedostress (τ^x) using the following formula (as done in Harrison and Chiodi 2009),

$$\tau^x = \rho_a C_d |U| u$$

Here, air density (ρ_a) is assigned the value of 1.25 kg m^{-3}, C_d is assumed to have the value of 1.3 10^{-3}, $|U|$ is the magnitude of the 10-m wind vector and u is its zonal component.

To examine the effects of MJO wind stress anomalies on tropical Pacific SST, pseudo-event wind stress anomalies are formed from the sequence of MJO-phase composites (1 through 8). Each phase is prescribed to last 5 days, for a total of 40 days of anomaly forcing. Wind stress anomalies are applied to the model beginning with phase 1. The effects of using a different starting point (e.g. start with phase 6 and proceed in modulo order) were examined but are not discussed since they produce results qualitatively similar to those described herein. We have also experimented with prescribing the duration of the phase according to the actual time spent in each in the identified MJO events, but find results qualitatively similar to those produced by the 5-day duration composites are yielded in this case (as described in the results section).

For comparison, the effects of WWE-type wind stress anomalies are also examined with OGCM experiments following the methods of Harrison and Chiodi (2009), in which case the respective daily WWE-wind stress anomaly composites from event-day -20 to +20 are applied to the model. In both the MJO and WWE experiments, the model is first spun up to realistic climatoligical conditions (as described in detail in Harrison et al. 2009), and the wind stress-driven SSTAs are determined by comparing the model SST fields produced by integrating the model with and without the respective wind stress anomalies.

3. Observed SSTA changes following MJO events

We identified 62 MJO events that occurred in the 1986-2010 period during ENSO-neutral conditions and lasted at least 20 days, the vast majority of which (58) reached their westerly surface phase (i.e. phases 6, 7, and 8). The composite change in SSTA following these 58 MJO events, keyed on the beginning of the westerly surface phase (phase 6), are shown in the left-hand-side panels of Figure 1, with shading where the composited SSTA-changes are statistically significant ($p > 0.95$) based on Monte-Carlo bootstrap methods. The composite SSTA-change 20 days after the start of MJO phase 6 (upper left panel) shows little statistically significant anomaly that persists to the following +40 day composite, which, like the +20 day case, shows rather little change from starting conditions in the tropical Pacific. The subsequent +60 day composite shows some warming in the eastern equatorial Pacific between 140°W and 100°W with amplitudes of 0.2-0.4°C, which are not yet statistically significant. This warming pattern intensifies by the +80 day composite, however, becoming statistically significant then.

Of these 58 MJO events, 41 have an embedded WWE, and 17 do not. The composite changes in SSTA following MJOs without a WWE are shown in the middle column of Figure 1. Examination clearly shows that, in an average sense, statistically significant warming does not follow the 17 MJO events that do not contain a WWE.

On the other hand, the SSTA-changes that follow MJO events containing at least one W-, C-, or E-type WWE (right-hand-side panels of Fig. 1) produce some isolated regions of warming in the central equatorial Pacific in the day +20 composite, that can be seen to broaden to an elongated pattern of >0.2°C warming located between the Dateline and about 110°W in the +40 and +60 day composites, and continues to intensify as it moves eastward during the next weeks, resulting in substantial (0.4-0.6°C) and statistically significant warming in the eastern equatorial Pacific by the day +80 composite.

We also used the methods of Maloney and Hartmann (1998; MH98 hereafter) to identify 68 MJO events that occurring in ENSO-neutral conditions during the study period. The corresponding day +80 composites of SSTA-change are shown in Figure 2 for the 47 MH98-identified MJO events that do and 21 Mh98-identified MJO events that do not contain a WWE. The corresponding +80 day WH04-based SSTA-change composites (as discussed above) are also shown in this figure for comparison. Based on the MH98 definition, very little equatorial Pacific warming is seen following the identified MJO events regardless of whether they do or do not contain a WWE.

4. Observed SSTA-change following WWEs

Ninety-eight W-type WWEs are identified in the 1986-2010 period that occurred during ENSO-neutral conditions. The composite changes in SSTA that follow these WWEs are shown in the left-hand-column of Figure 3, where it can be seen that a small (< 0.2°C), but statistically significant warming occurs in the central equatorial Pacific in the first 20 days following these WWEs, that intensifies and moves eastward over the following weeks, resulting in a coherent pattern of equatorially trapped warming in the +80 day composite that spans much of the central and eastern equatorial Pacific and has amplitudes > 0.4°C in the eastern equatorial Pacific.

The composite SSTA changes following C-type and E-type WWEs that occurred in ENSO-neutral conditions over the same 25-year period are shown in the middle- and right-hand column of Figure 3, respectively (based on 105 C-type WWEs and 52 E-type WWEs). Some differences and similarities between these and the W-type composite are evident. For example, the warming amplitudes following the C-type (E-type) events are somewhat smaller (larger) than seen in the W-type case, and the coherent cooling seen west of the Dateline in the W-type composites is not evident to the same degree in the C- and E-type composites. However, the same basic picture emerges from each of these three composite-sequences; in an average sense, warming anomalies with amplitudes of a few to several tenths of a degree C appear in the central and eastern equatorial Pacific following each of these three types of WWEs.

For reference, the +80 day changes in NIÑO3 that follow each of these types of WWEs are listed in Table 1. Results for all WWEs occurring in ENSO-neutral conditions show that on average, the NIÑO3 SSTA index warms by a statistically significant ($p > 0.95$) few tenths of a degree C following each of these three types of WWEs (1st column). Results also show that warming is seen regardless of whether the WWEs occur during MJO-events (2nd column) or not (3rd column), and although somewhat larger warming amplitudes were seen following the WWEs that occurred during MJO-events, especially in the E-type composite, the differences between these and the composite NIÑO3 changes following WWEs that did not occur during an MJO-event are not statistically significant at the 90% confidence level. At lower levels (e.g. 80%), the E-type difference, which is based on the fewest number of samples, may become statistically significant, but the differences seen for the W- and C- types remain well within the range expected from the effects of random selection (even at the 66% confidence level).

5. Model response to composite MJO wind anomalies

The effects of MJO wind stress anomalies applied to a realistic ocean general circulation model are examined in the experiments described here. In each experiment, we first formed composite wind stress anomalies for each phase of the MJO based on the daily anomalies seen in the indentified MJO-events that occurred in ENSO-neutral conditions. Next we form a pseudo-MJO-event composite based on the 8 different phase-composites by prescribing that each phase lasts for 5 days. The resulting 40-day wind stress anomaly composite (shown atop Figure 4) is then applied to the model. We have also looked at what happens when the phase duration is specified according to the time spent, on average, in each phase during the identified MJO events, but found that the results are very similar to those produced by the 5-day phase composite (as discussed further, below).

Preliminary experiments showed that the model results remain qualitatively similar regardless of which season the wind stress composites are applied in. For brevity, we discuss results from a single case (June), in which the wind composites are applied during a season typically associated with the El Niño "onset" stage (Larkin and Harrison, 2002). The conclusions reached herein are not affected by the choice of month in which the wind anomalies are applied to the model.

We discuss results from 3 different experiments that are procedurally similar except that in the first, all 62 ENSO-neutral MJO events that are identified using the WH04 index are used to form the pseudo-event composite. In the second, just those MJO-events with embedded W-, C-, or E-type WWEs are used. And in the third, only the MJO-events that do not contain a WWE are used.

The evolution of SSTA in the months following the application of the composite based on all of the 62 MJO-events that occurred in ENSO-neutral conditions is shown in the left-hand-side panels of Figure 5, where it can be seen that only relatively modest amplitude (< 0.2°C) changes in SST, are driven in the model and last until days +60 or +80 in this case.

The SSTAs driven by the composite based on MJO-events that do not contain any WWEs are shown in the middle-column of panels of in Figure 5, and the composite based on MJO-events that contain either a W-, C-, or E-type WWEs are shown in the panels on the right-hand-side of this figure. Comparison of these results reveals change in character depending on whether the original MJO events did or did not contain a WWE. The MJO wind stress composite with a WWE produces a patch of small amplitude (0.1-0.2°C) equatorially trapped warming near the Dateline that can be seen in the +40 day panel (right-hand column, 2nd row), which is followed by a somewhat stronger, albeit still relatively modest (0.2-0.4°C) patch of warming in the cold tongue region (e.g. ~140°W to 110°W) in the +60 and +80day panels (right-hand column, bottom two rows). In contrast, the experiment based on the MJO-events that do not contain a WWE (middle column of panels) does not show warming in these regions at these times.

Comparison with the companion SSTA-changes seen following MJO events in the observations show some differences and similarities in each case. In the 62-MJO-event case, the warming seen in the composite of observed SSTA changes (Fig. 1, left-hand-side) shows somewhat larger amplitude warming at +80 days compared to the model. This could be due to the aliasing of other sources of warming (e.g. previous WWEs), errors in the composite wind stress, or model biases. The observed SSTA changes following MJOs with WWEs (Fig. 1, right-hand column) shows a small patch of warming in the 110°W-100°W region in the +20 day composite that is not reproduced in the model (Fig. 5, right-hand-column), that could likewise be due to, for example, the effect of several prior but closely timed WWEs. Also, the cooling amplitudes seen in the model following a MJO-wind anomaly composite that does not contain a WWE (Fig. 5, middle-column), which peak in the 0.6-0.8°C range, are larger in magnitude (by about 0.2°C) and broader scale than the cooling seen in the companion +20 and +40 day observation-based SSTA-change composites (Fig. 1, middle-column). Even with these differences, however, the MJO model experiments and composite analysis have in common the fact that, in each case, the SSTA-changes that include the effects of WWEs lead to cold-tongue warming on the order of a few tenths of a degree following the wind event. The results for MJO events that do not contain a WWE, however, do not show this type of warming.

As mentioned above, we have also repeated the experiments discussed above after modifying the idealized MJO composite so that the number of days spent in phase varies (at 6 hour resolution) according to the average time spent in each phase in the identified MJO events. The average duration across all phases turns out to be 4.5 days, ranging from 5.5 days in phase 6 to 3 days in phase 4. Qualitatively similar results are obtained in the varying- and equal-duration cases (c.f. Appendix Figure C1). The character of SSTA produced in the model depends much more on whether the MJO does or does not contain a WWE than it does on these types of details of the observed MJO phase-duration.

6. Model response to WWE wind stress anomaly

The SSTA anomalies driven in the ocean model by composite W-, C- and E-type WWE wind stress anomalies can be seen in Figure 6. As in the MJO base-case, the wind anomalies in these experiments are applied for 40 days. For each WWE type, equatorially trapped warming on the order of a few tenths of a degree C is seen following the WWE in the equatorial central Pacific and later in the equatorial eastern Pacific, at somewhat greater amplitude than seen earlier around the Dateline. It is notable that this set of composite wind stress anomalies, which is keyed specifically on WWEs rather than the MJO phases, drives warming patterns that are more coherent and larger than, but nonetheless similar in character to those driven in the model by the "MJO-with-WWE" wind stress composites. For example, in each case, an initial near-equatorial warming is seen around the Dateline (i.e. in the +20 or +40 day panels) that is followed (at +60 or +80 days) by stronger warming in the equatorial eastern central Pacific. Some differences are noticeable also. Less initial warming is seen in the MJO-with-WWE model experiments than is seen in the experiments that key specifically on WWEs, which perhaps is not surprising given that the applied MJO wind anomaly composite begins in its surface-easterly wind anomaly phase and such easterlies, which should be expected to cool the central and eastern Pacific, are not, in general, a characteristic of WWE wind anomalies.

That oceanic waveguide warming is seen in the model following the application of W-, C- and E-type wind anomaly composites, as well as the MJO+WWE composite, but not seen following the MJO-without-WWE wind anomalies shows that in these model experiments it is the WWE wind anomalies that drive cold tongue warming, not the MJO.

Comparison of the WWE-based model (Fig. 6) and observational results (Fig. 3) reveals some similarities and differences. But keeping in mind the many possible reasons for discrepancies of ~0.2°C (e.g. wind stress error, model bias, aliasing SSTA changes caused by other events in the observations), it can be said that the upper ocean circulation changes driven in the model by the composite WWE wind anomalies cause warming of SSTA in the central and eastern equatorial Pacific that is at least roughly consistent in terms of magnitude, timing and character, with the changes observed to follow these types of WWEs in an average sense. This is consistent with results previously discussed by Vecchi and Harrison (2000) and Harrison and Chiodi (2009).

We also looked at the effects of using WWE wind anomalies composited over just those WWEs that occurred and did not occur during an MJO-event, but found that very similar SSTAs were driven in each case. This can be seen in Figure 7, where the equatorial SSTA changes following the application of two C-type WWE composites (embedded in MJO and not) are shown in the time-longitude perspective. We also ran the corresponding W- and E-type experiments, and found that similarly small differences in SSTAs are seen in these cases between the MJO-embedded and not-embedded composites (not shown for brevity). The state of the MJO does not appear to importantly affect the ability of the WWEs to cause warming of the central and eastern equatorial Pacific.

7. Model diagnostics

In this section we further explore the oceanic processes that allow equatorially centered WWEs to warm the oceanic waveguide in the several months following their occurrence. We have examined the model behavior following the application of each type of WWE discussed here (W, C, and E) and found qualitatively similar results in this case. Thus, we have chosen to present just one set of results here (the C-type), rather than unnecessarily lengthen the manuscript.

Panel (a) of Figure 8 shows, again in the time-longitude perspective, the equatorial upper ocean (0-50m and 2°S-2°N average) temperature anomaly that is produced in the model following the application of a C-type WWE wind anomaly. Panel (b) shows the result of integrating the sum of each of the terms in the model heat budget (e.g. horizontal and vertical advection of the temperature gradient, surface heat flux, diffusion, etc). The close correspondence between the temperature anomaly patterns shown in Panels (a) and (b) confirms that the terms we examine accurately represent the warming actually seen in the model. In Panels (c) and (d), the anomaly seen in Panel (b) is separated into two components; that driven by changes in ocean circulation (Panel c) and that produced by other processes (e.g. vertical diffusion) that we have chosen to sum after finding that the anomaly seen in Panel (a) is driven predominantly by the circulation changes. In Panels (e) through (h) we further examine these circulation anomaly effects. The temperature tendency that produces the anomaly seen in Panel (c), that is, the 1st derivative of the advection-driven temperature anomaly, is shown in Panel (e). In Panels (f) and (g) this temperature tendency is split into parts driven by horizontal and vertical changes in circulation, respectively. This reveals that the horizontal and vertical advection terms (specifically the horizontal and vertical heat flux divergence anomalies) are each much larger in amplitude than the net temperature tendency seen in the model, but have very similar oppositely-signed patterns. Thus, the warming seen in the model results from there being a small imbalance between these two much larger, nearly-compensating terms. To more clearly gauge which component drives/damps the net change in temperature, in Panel (h) we have shaded the time-and-space where there is > 0.015 °C/day-amplitude net warming. The shading hue and value is chosen as follows: red if warming > cooling, blue otherwise; dark if horizontal > vertical, light otherwise. We thereby see that the initial (June-July) near-Dateline warming occurs because the horizontal (warming) component dominates the vertical (cooling) component then. The resulting warm-SSTA in this location then subsides mainly because of the effects of vertical (cooling) advection. Further east, the larger-amplitude warming that occurs in the cold-tongue can also be seen to be mainly dominated by the effects of horizontal (warming) advection, although the vertical and horizontal components do switch roles in the later warming stages in the latitudes between 140°W and 110°W. This eastern-Pacific patch of warm SSTA later diminishes in amplitude due to the effects of horizontal (cooling) circulation changes. Examining the model current anomalies, we have confirmed that the horizontal advection anomalies discussed above are driven mainly by changes in the zonal, rather than meridional component (not shown for brevity).

The same type of diagnostic-analysis has been performed on a model experiment in which a composite MJO wind stress anomaly, based just on MJO events that contain a C-type WWE, was used to drive the model. In this case, an initial June/July cooling is seen in the eastern-Pacific (approx. 140°W to 80°W) due to the presence of the MJO-related surface easterlies in the applied wind composite. Following this initial cooling, however, the diagnostic results (Fig. 9) reveal that the ocean processes that create warm upper ocean temperatures following this MJO+ C-type WWE wind anomaly are similar in character to those that cause the warming in the C-type WWE case discussed above. Here again, the cold-tongue warming that is seen 2-3 months after the application of the wind anomaly is mainly driven by anomalous horizontal temperature advection. It may be noted, however, that in this case the vertical advection component also contributes to some of the later warming seen in the 140°W-110°W longitude band (with horizontal advection in this case reversing from its otherwise warming-tendency).

Cold tongue warming like that seen following a WWE or MJO+WWE is not seen following the application of the composite MJO wind anomaly that is based on just the events that do not contain an embedded WWE (Fig. 10). As in the two experiments discussed above, however, the temperature changes that are seen in this case are still initiated and mainly driven by wind-driven changes in horizontal advection.

In summary, it is mainly the wind-driven changes in the horizontal (zonal) ocean heat flux divergence that is responsible for the equatorial warming that is seen in the model following the application of WWE-related wind anomalies. It should be recognized, however, that the equatorial warming that occurs in the model results from a small imbalance between two large (horizontal heating + vertical cooling) components.

7. Distribution of MJO-events and WWEs

In this section we more closely examine the relationship between the timing of the MJO and WWEs, focusing mainly, but not exclusively, on the events occurring in ENSO-neutral conditions. Our intent is to determine whether the historical record supports WWEs being considered characteristic of – perhaps implying a causal relationship with - the MJO, as has previously been suggested (e.g. Seiki and Takayabu, 2007), or whether it is best to think of WWEs and MJO-events as distinctly distributed events. To do this we determine the numbers of MJO events that do and do not contain a WWE, as well as the numbers of WWEs that occur and do not occur during an MJO event. The historical distributions of events will be compared to those produced in a Monte Carlo simulation that randomly distributes the same number of events throughout the period(s) considered to identify any characteristics of the observed distributions that cannot be easily explained by the effects of random selection and therefore could be suggestive of a causal relationship.

The respective categories of MJO and WWEs are defined as follows. An MJO event that contains a WWE is one in which the start-day of at least one W-, C- or E-type WWE occurs during it. The remaining MJO events do not contain a WWE. As described in the methods section, WWEs are defined as days in which the defining-region average wind speed anomaly is > 2 m/s for at least 3 consecutive days, with the WWE start-day being the first of these days. A WWE that occurs during an MJO-event is one in which the start-day occurs during one of the identified MJO events. The remaining WWEs do not occur during an MJO event.

For each ENSO-condition considered, there are some MJO events that do and some that do not contain a WWE, but not in equal numbers (Table 2). Over all ENSO-conditions, the number of MJO events with a WWE exceeds the number that do not contain a WWE, but what does this result say about whether or not the chance of seeing a WWE is affected by the state of the MJO? To decide this properly, the characteristic duration and frequency of the MJO, as well as frequency of WWEs must be taken into account.

In ENSO-neutral conditions there were 62 MJO events identified, including 42 that contain a WWE and 20 that do not. The average duration of these MJO events is 34 days, with the shortest lasting 20 days (one of our event-criteria), and the longest being a rather impressive sequence of 153 days in which phases 1-8 were cycled-through three times. Based on the definitions used here, the MJO was in “event-state” 40% of the time that the NIÑO3 index had magnitude < 0.75°C in the 1986-2010 period. During this same time there were 256 WWEs identified with start-days in ENSO-neutral conditions. We performed bootstrap-Monte Carlo simulations (N=10000) to test whether the observed fraction of MJO events with/without a WWE is unusual compared to those expected based on a purely random scattering of this number of WWEs about the identified time-history of MJO activity. The average value, 5%- and 95%-confidence levels from the Monte Carlo simulations are shown in Figure 11, where it can be seen that the observed number of MJO events that contain a WWE (42) is very close to the most likely value (43 - to the nearest whole number), and well within the 5% (37) and 95% (48) confidence levels. It follows that the observed number of MJO events that do not contain a WWE also fits easily within the simulated (random) distribution. Thus, the null-hypothesis, that WWE-likelihood remains the same whether or not an MJO-event occurs, holds for ENSO-neutral conditions.

It is evident from the values in Table 2 that the fraction of MJO events with a WWE greatly increases moving from ENSO-neutral to warm-ENSO conditions, during which time 25 out of 26 MJO were observed to contain a WWE. It came initially at some surprise to the authors to find that results from the same type of Monte Carlo simulation as described above, except applied to the warm-ENSO (NIÑO3 > 0.75°C) portion of the record, show that even this result is not statistically significant; that is, not much different than should be expected based on random selection of WWE start-times. This can be understood by considering that although the fractions of time that the MJO is in “event-state” in both ENSO-neutral and –warm conditions are about the same, the frequency of WWEs increases substantially moving from neutral to warm-ENSO conditions. Specifically, the WWE frequency increases from ~1.3 per month (256 WWEs in 5784 days) in ENSO-neutral, to ~2.4 per month (136 WWEs in 1744 days) in warm-ENSO conditions. This increase in WWE frequency as the ENSO SSTAs warm is consistent with the findings of Harrison and Vecchi (1997) and Vecchi and Harrison (2000), which were based on a substantially shorter record, along with the many other aforementioned studies (e.g. Lengaigne *et al.* 2004; Vecchi *et al.* 2006; Eisenman et al. 2005; Gebbie et al. 2007; Gebbie and Tziperman, 2009.a,b) that have examined the dependence of WWE frequency on ENSO-state. Due to the relatively high frequency of WWEs in warm-ENSO conditions, it simply becomes rather difficult to randomly choose an MJO-event-sized time-span that does not contain at least 1 WWE in warm ENSO-conditions. The most common Monte-Carlo result in this case was finding that 23 of the 26 MJO events contained at least one randomly-scattered WWE. Although the observed number (25) is slightly larger, it is not statistically significant at standard ($p > 0.8$) confidence levels.

As a point of comparison, it is notable that results comparable to Seiki and Takayabu's (2007) finding, based on different MJO and WWE definitions than used here, that the fraction of MJO events that contain WWEs tends to increase with MJO amplitude (c.f. their Figure 14) can also be seen in the distribution of events discussed here. When the 62 ENSO-neutral MJO events we identify are ranked based on the maximum daily MJO-amplitude attained during the event, for example, it is revealed that 9 of the top 10, and all 5 of the top 5-ranked MJO-events contain WWEs. Before imputing meaning to this result, however, it is important to test the null hypothesis that such a result can easily be explained by chance. In this case, Monte Carlo results again show that it can. It bears noting that another characteristic of MJOs that increases with amplitude is their length; there is about a factor of 2 difference between the average lengths of all 62 MJO events (33 days) and the top-ranked events (61 and 78 days in the top-10 and top-5 cases, respectively). It is simply difficult to randomly choose such (longer-than-average) lengths of time without bracketing at least one of the 256 WWEs observed in the period considered. In each case (top-5 and top-10), there was a better than 50% chance that the number of MJO-with-WWE events found by the Monte Carlo model met or exceeded the numbers (9/10, and 5/5) seen in the observed record. Thus, this is not a statistically significant relationship. Our results therefore do not support the Seiki et al. (2007) hypothesis that large-amplitude MJO events are especially conducive to WWEs.

We have also used Monte Carlo methods to examine the related question of whether the distribution of WWEs with respect to MJO-state shows any significant deviations from that expected based on chance alone. The results we find in this case are consistent with those discussed above in that both the total number of WWEs that do (92) and do not (164) occur during the MJO events identified in ENSO-neutral conditions (Fig. 12; yellow bar and inset orange bar, respectively) are not significantly different from the values expected based on random chance alone.

Upon closer inspection, however, we do see that when they co-occur, WWEs tend to avoid the phases of the MJO with surface easterlies in the tropical Pacific (esp. phases 1, 2 and 3) and instead frequent the later westerly phases (esp. phases 6 and 8). Although it may be at first tempting to some to draw conclusions based just on this increase in WWE-frequency in phases 6 and 8, it must also be recognized that the commensurate decrease in WWE frequency during the surface easterly MJO phases means that the overall likelihood of seeing a WWE is not significantly changed by the presence of the MJO (unless the MJO is somehow able to start and end in its surface westerly phase without passing through its surface easterly phases – which is not its characteristic behavior).

In summary, we find that when they do co-occur, there is a tendency for the WWEs to frequent the surface westerly phases of the MJO and avoid, in nearly equal numbers, the surface easterly phases of the MJO such that that the overall likelihood of seeing a WWE is not changed by the presence of the MJO, even in extreme MJO-amplitude cases. This finding is confirmed when MJO events are identified using the Maloney and Hartmann (1998) MJO definition (Figure 13).

8. Summary and Discussion

Our composites of SSTA changes observed over the last 25 years show that anomalous waveguide warming, upwards of a few tenths of a degree is seen, in an average sense, following the W- C- and E-type WWEs that occurred during ENSO-neutral conditions. Over this time, warming-anomalies with similar amplitudes and pattern are seen in the composites regardless of whether they include just WWEs that do or do not occur during an MJO event.

This same type of warming-anomaly is seen, in an average sense, following the contemporaneous MJO events that contain embedded WWEs, but is not seen following the MJO events that do not have embedded WWEs.

Integration of composite WWE and MJO wind stress anomalies in a realistic primitive-equation model of the upper tropical Pacific is able to reproduce these results, in the sense that composite WWE wind stresses, and (to a lesser extent) wind stress composites from MJOs that contain WWEs drive comparable warm-SSTA anomalies in the model. However, this type of warming is not seen in the model following composite MJO-events that do not contain embedded WWEs.

Together, these results show that it is the WWE wind stress anomalies, rather than the MJO, that are important to the onset of El Niño events. This confirms the findings of Vecchi (2000), with a near doubling of period, while, on the other hand, contradicting some previous hypotheses that the MJO itself plays an important role in initiating an El Niño event. Although direct comparison between previous studies of MJO-effects on SSTA and ours is made difficult by the fact that different MJO definitions have generally been used in each case (c.f. Kessler and Kleeman 2000; Zhang and Gottshalck, 2002; Hendon et al. 2007; Seiki and Takayabu 2007; Seiki et al. 2009; Kapur et al. 2011), we suggest that the results of this study, which dissects the inter-relationships between each class of wind event and the changes in waveguide SSTA that follow them, nonetheless provide a generally useful perspective from which to better understand the seemingly disparate claims about WWE and MJO effects that exist in the published literature.

The co-occurrence of MJO and westerly wind events, as defined here, is common enough that it is not difficult to find MJO events with embedded WWEs regardless of the definitions used, and it is evident that waveguide warming, like that which follows solo-WWEs, will often be seen following the MJO events that contain a WWE. Further, it is reasonable to expect that different MJO definitions will capture relatively more or less of the effects of these WWEs, but the results discussed here strongly suggest that even the most skillful prediction of the state of the MJO will not be useful in predicting the development of El Niño events since the MJO does not itself contribute to waveguide warming, nor does it affect the net chances, even in the case of extreme-amplitude MJO events, of seeing a WWE.

On the other hand, our results are consistent with (though do not explain) previous findings that WWE frequency increases with the transition from ENSO-neutral to warm-ENSO conditions, thereby increasing the influence of WWEs on ENSO (Harrison and Vecchi 1997; Vecchi and Harrison 2000; Lengaigne *et al.* 2004; Eisenman et al. 2005; Vecchi *et al.* 2006; Gebbie et al. 2007; Gebbie and Tziperman, 2009.a,b; Harrison and Chiodi, 2009). That is, although WWEs are high frequency and the details of each event have a substantial stochastic component, the strong relationship between WWE frequency and ENSO-state makes WWEs, to a large degree, an element of the "slow" coupled ocean-atmosphere processes that help drive and maintain equatorial Pacific waveguide warming during El Niño events. WWEs are not best though of as external "additive" noise.

Thus, forming a better understanding of the sources and predictability of WWEs remains an avenue improving our understanding of the mechanisms for initiation, and potential predictability of an El Niño event, but it does not seem that effort to better understand the MJO, though potentially quite useful in many other important respects, will provide this.

Appendix A: MJO and WWE composite wind anomalies

Figure A1, herein, shows the composite wind anomalies for each phase of the MJO. In this case the composites are averages of the daily wind anomalies for each day that the MJO amplitude was > 1and the MJO was in the given phase. Only ENSO-neutral days are considered in this case.

Figure A2 shows the Day 0 composite wind anomalies for the W-, C- and E- type WWEs that occurred in ENSO-neutral conditions in the 1986-2010 period. In each case, the anomalies with statistically significant zonal components are marked by bold vectors.

Appendix B: Monte Carlo methods

This appendix describes the methods used for determining whether or not the anomaly magnitudes seen in the composites of observed variables (e.g. SSTA-changes following the MJO and WWEs, event composite wind anomalies) can easily be obtained by random selection of dates, or instead, whether they are statistically significant. This process is conceptually straightforward in that the compositing procedure used for the observations is simply repeated in the Monte Carlo simulation, except that in the Monte Carlo case, the composited days are chosen randomly. Specifically, a number of days are randomly chosen from the distribution of days considered (e.g. all those in which |NIÑO3| < 0.75°C) and averaged, repeatedly, to build up a distribution of possible outcomes, to which the observed result is compared. If the observed result lies at the narrow tail of this distribution (e.g. $p > 0.95$) then it is considered statistically significant. If the likelihood of getting the observed result by chance is higher than this, they are not.

In such statistical methods it is often important that the number of effectively independent samples contained in the actual and bootstrap-composites be consistent with one another. Traditionally, the number of "degrees of freedom" in the actual composite has been determined as a function of the sample autocorrelation (ACF) function (e.g. Leith 1973). Here, we use a procedure that yields results consistent with the traditional methods, but avoids the burden of calculating the ACF at each grid point considered. Instead, we rely on the observed frequency of events to reproduce the effects of any observations that may lie within an "effective time between independent samples". To do this we begin at a random date within the subset of dates considered, and then select samples from the (modulo) historical record, with sample-to-sample time lags randomly chosen from the observed time-lags that lie within the continuous ENSO-neutral periods, until the bootstrap and observed SSTA-change composites contain the same number of samples. In this way, the average effects of closely-spaced observations, that is, observations that occur too close together in time to be considered independent of one another, is reproduced in the bootstrap procedure in a manner consistent with the observations. We chose this method since it alleviates the computationally intensive need to determine autocorrelation characteristics for each of the (spatially varying) fields considered. Trial has shown that the difference between including and not including these effects of closely-spaced observations on the estimated confidence intervals, though not negligible, can be neglected without fundamentally changing the results discussed here (i.e. the timings of the WWEs and MJO-events are such that each can almost be considered to be associated with an independent sample of the target variable).

Appendix C

The figure herein shows the results of applying an idealized MJO composite wind stress anomaly to the ocean model. The results in this figure were obtained by the same experimental procedure used to produce the results shown in Figure 5, except in this case the specified MJO phase-duration varies according to the average duration observed in the identified MJO events, which ranges from 3 to 5.5 days and is 4.5 days, on average.

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Figure. 1. Composite SSTA change following the MJO events that occurred in ENSO-neutral conditions (|NIÑO3|<0.75°C) from 1986 to 2010. Results shown separately for all 58 ENSO-neutral MJO events (left), the 17 MJO events that do not contain an embedded WWE (middle) and the 41 that do contain a WWE (right).

Figure. 2. Upper panels: Same as in the +80 days panels shown in Fig. 1, which are based on the Wheeler and Hendon (2004) MJO index. Lower panels: same as above, except in this case the MJO events are identified using the Maloney and Hartmann (1998) index.

Figure. 3. Composite SSTA-changes following W-type (left), C-type (middle) and E-type (right) WWEs that occurred in ENSO-neutral (|NIÑO3| < 0.75°C) conditions in the 1986-2010 period.

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Figure 6. Model SSTA following the application of a composite WWE wind stress anomaly.

Figure 7. Model SSTA following application of a C-type WWE wind anomaly. Only WWEs that occurred in ENSO-neutral and MJO-active (-inactive) conditions were used in the composite used to drive the anomaly seen in the upper (lower) panel.

Figure 8. Near-surface ocean heat budget diagnostics from a C-type WWE model experiment; a) 0-50m average heat content anomaly, b) time-change in heat content anomaly expressed in W/m^2, c) sum of the heat budget terms, d) sum of just circulation-related effects, e) surface heat flux anomaly effects, f) other terms (see text). Panels (g) and (h) show the contribution of the horizontal and vertical

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Figure 9. Same as in Fig. 8, except for the MJO + WWE model experiment.

Figure 10. Same as in Fig. 8, except for the MJO-without-WWE model experiment.

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Figure 12. The numbers of WWEs that do and do not occur during an MJO event, listed by phase (based on WWE start-date) for the co-occurring case. Horizontal lines are the p=0.95, expected, and p=0.05 values.

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Figure A1. Composite MJO wind anomalies. Bold arrows highlight anomalies that reach the 95% confidence level based on Monte-Carlo bootstrap methods.

Figure A2. Westerly wind event wind anomalies.

Figure C1. Model SSTA following the application of a (variable-phase-duration) composite MJO wind stress anomaly.

Tables

Table 1: NIÑO3 index change 80 days following a WWE that occurs in REG-SSTA conditions.

	All WWEs (°C)	MJO-Active (°C)	MJO-Inactive (°C)
W-type	0.24	0.29	0.21
C-type	0.18	0.22	0.16
E-type	0.31	0.41	0.17

Table 2: Distribution of MJO events by ENSO-state and WWE activity.

Number of MJO events			
	Total	with WWE	No WWE
All-time	113	76	37
ENSO-neutral	62	42	20
Warm-ENSO	26	25	1

Figures.

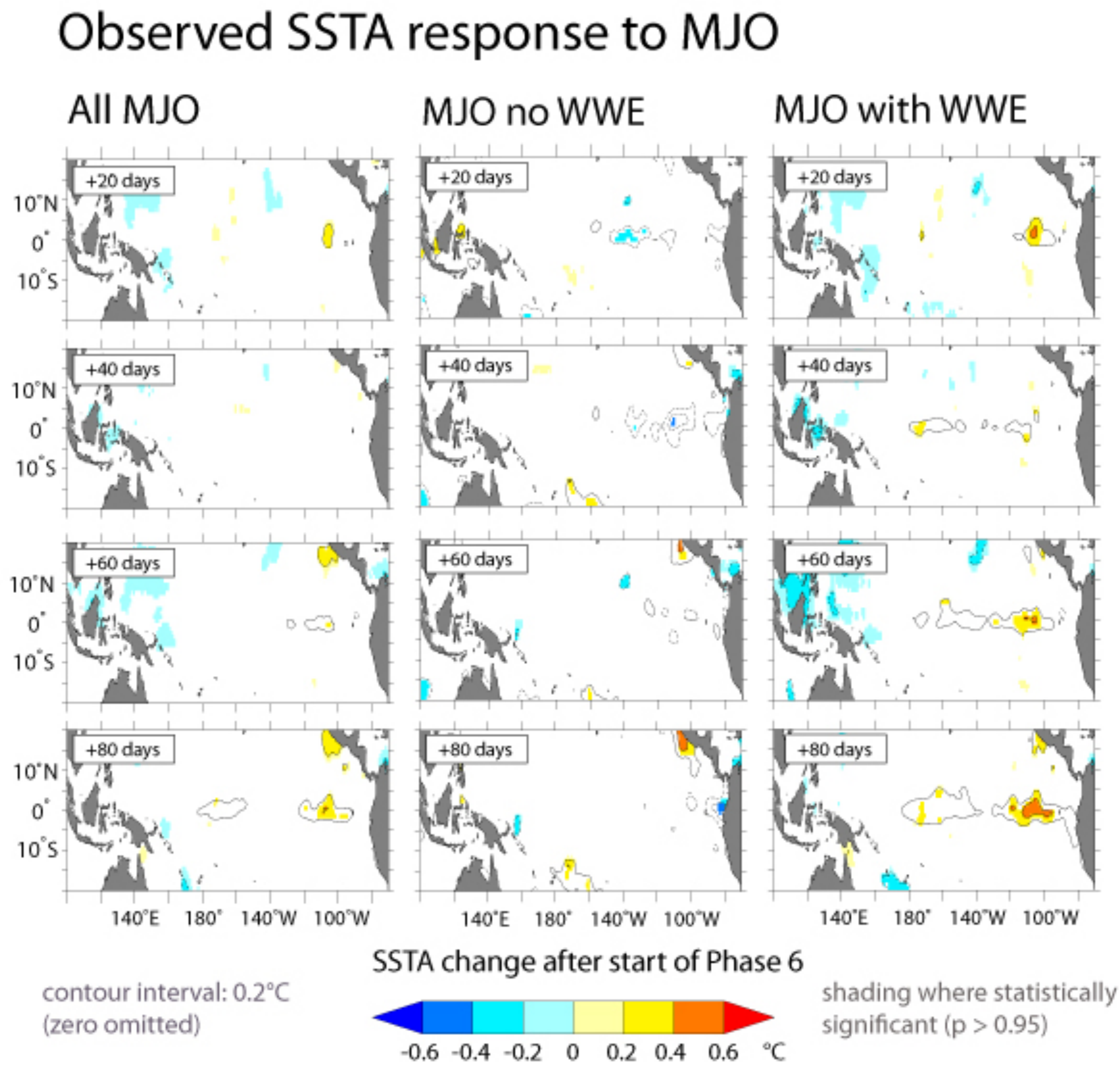


Figure. 1. Composite SSTA change following the MJO events that occurred in ENSO-neutral conditions (|NIÑO3|<0.75°C) from 1986 to 2010. Results shown separately for all 58 ENSO-neutral MJO events (left), the 17 MJO events that do not contain an embedded WWE (middle) and the 41 that do contain a WWE (right).

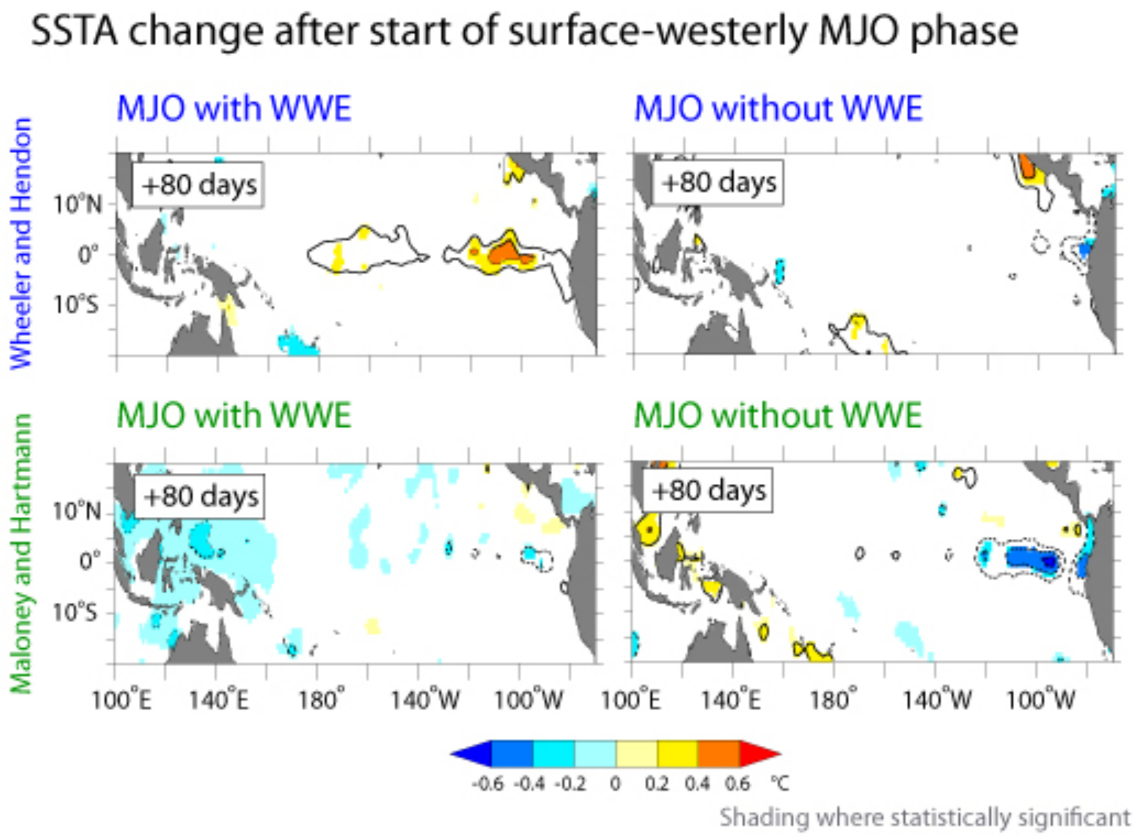


Figure 2. Upper panels: Same as in the +80 days panels shown in Fig. 1, which are based on the Wheeler and Hendon (2004) MJO index. Lower panels: same as above, except in this case the MJO events are identified using the Maloney and Hartmann (1998) index.

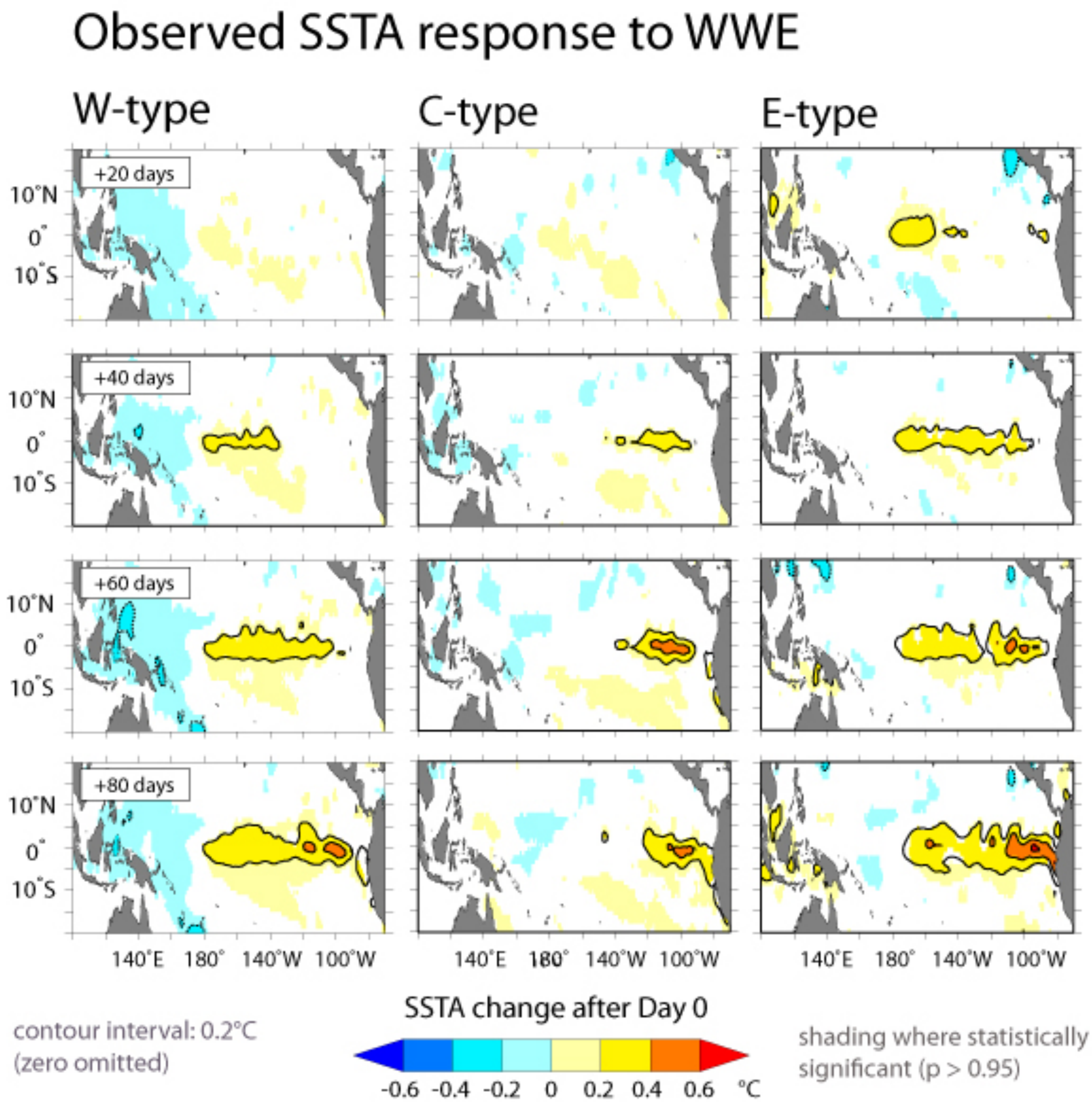


Figure 3. Composite SSTA-changes following W-type (left), C-type (middle) and E-type (right) WWEs that occurred in ENSO-neutral (|NIÑO3| < 0.75°C) conditions in the 1986-2010 period.

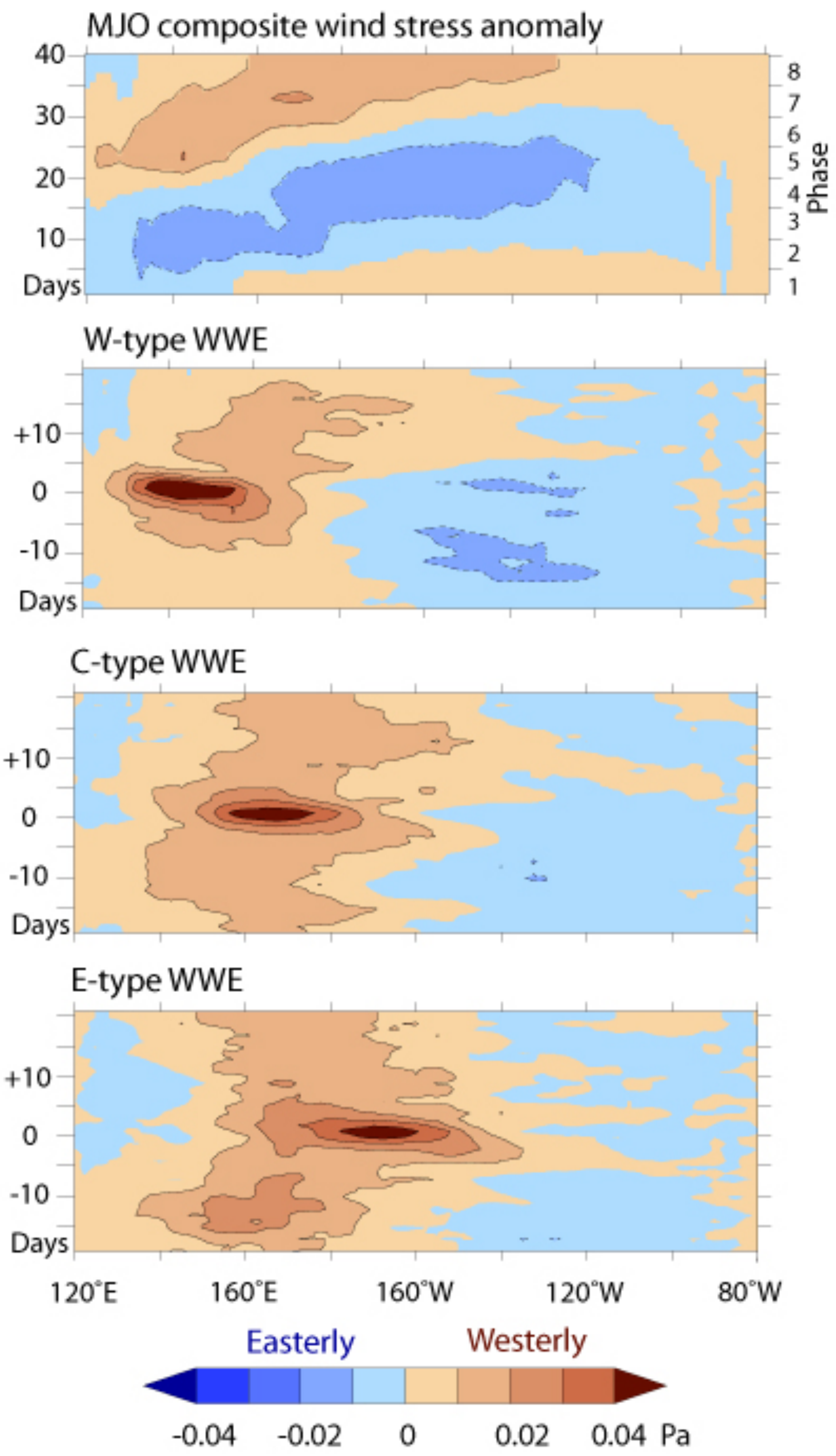


Figure 4. Composite MJO wind stress anomaly (upper panel) along with the W-type, C-type and E-type WWE composite wind stress anomalies (averaged over 2°S-2°N).

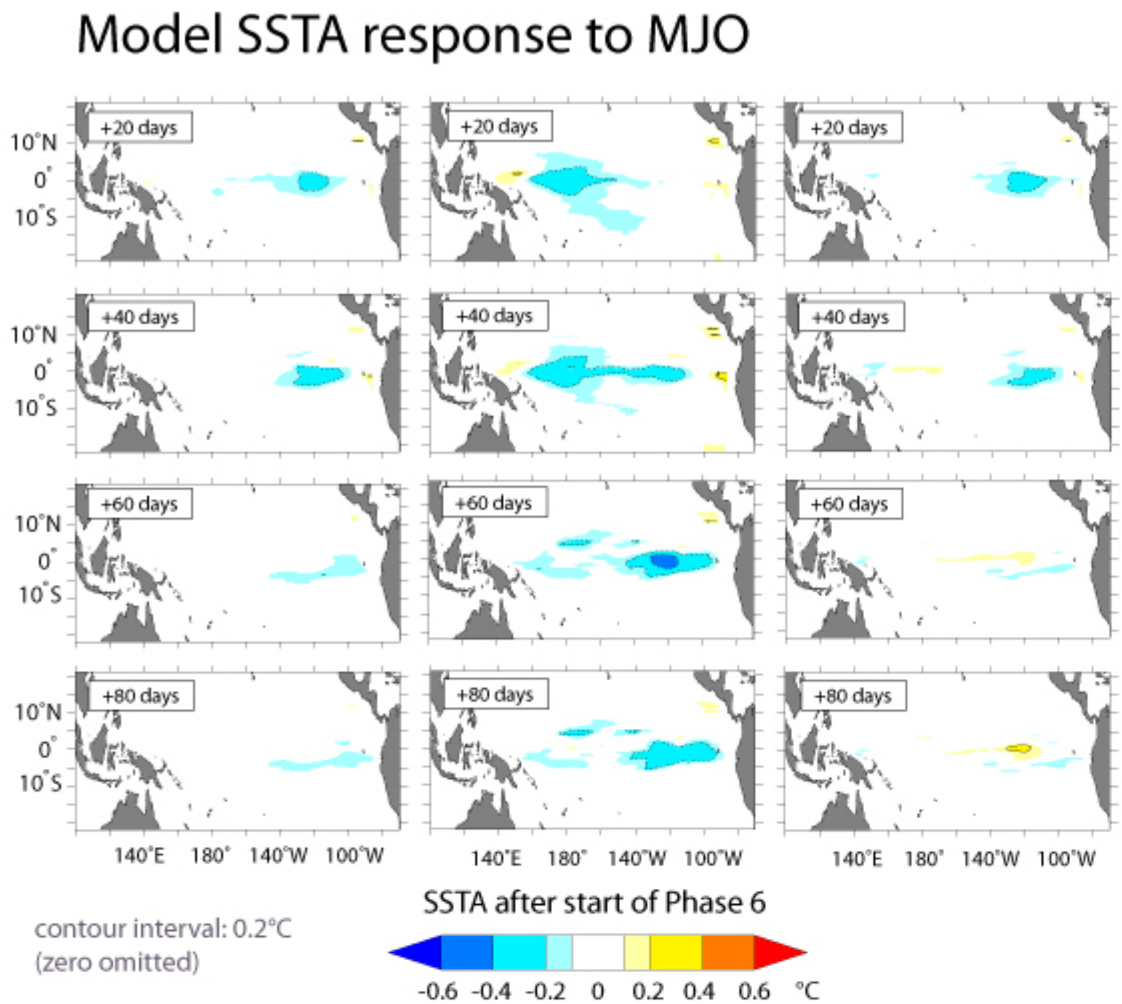


Figure 5. Change in model SSTA following the application of the composite MJO wind stress anomaly.

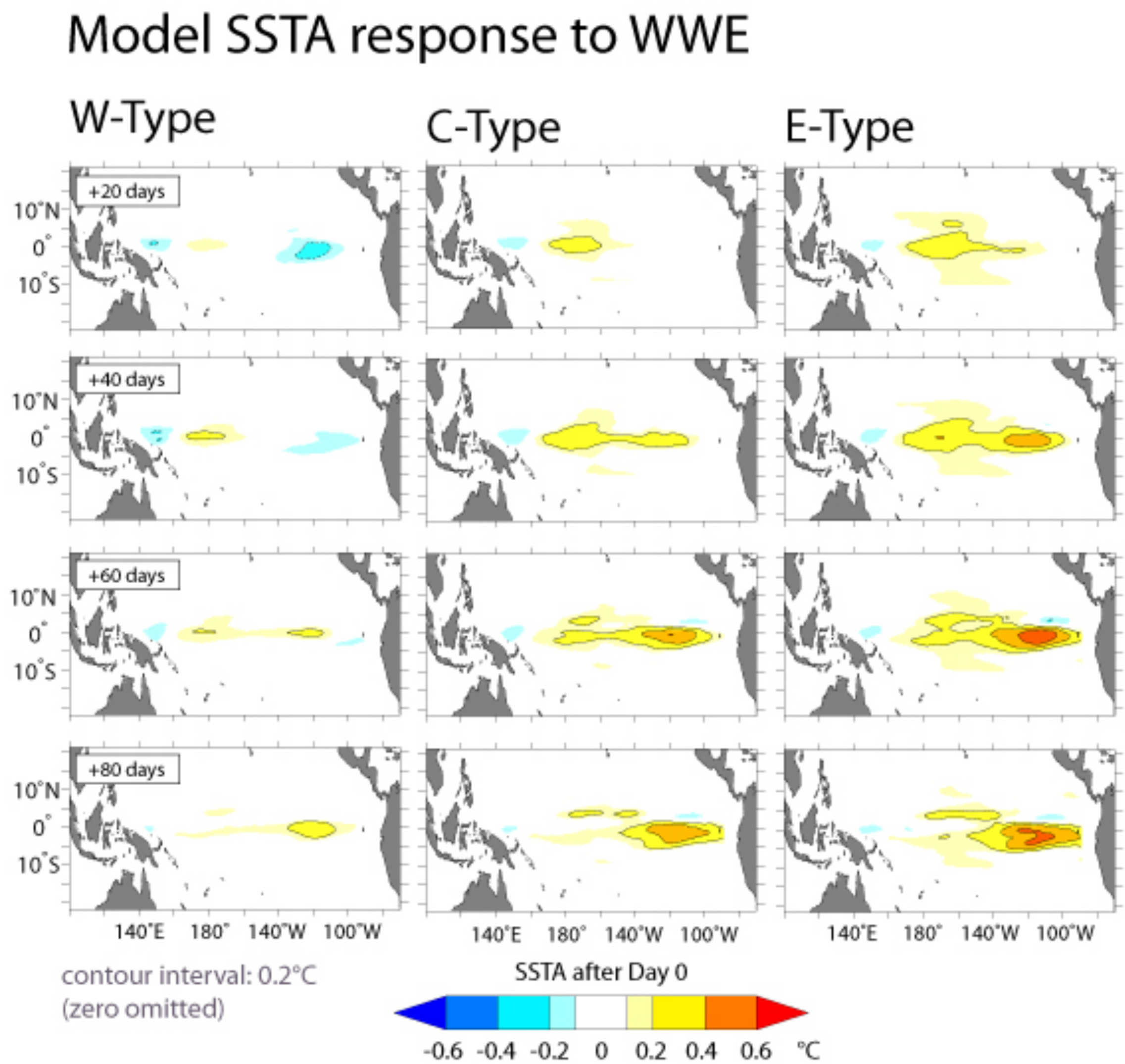


Figure 6. Model SSTA following the application of a composite WWE wind stress anomaly.

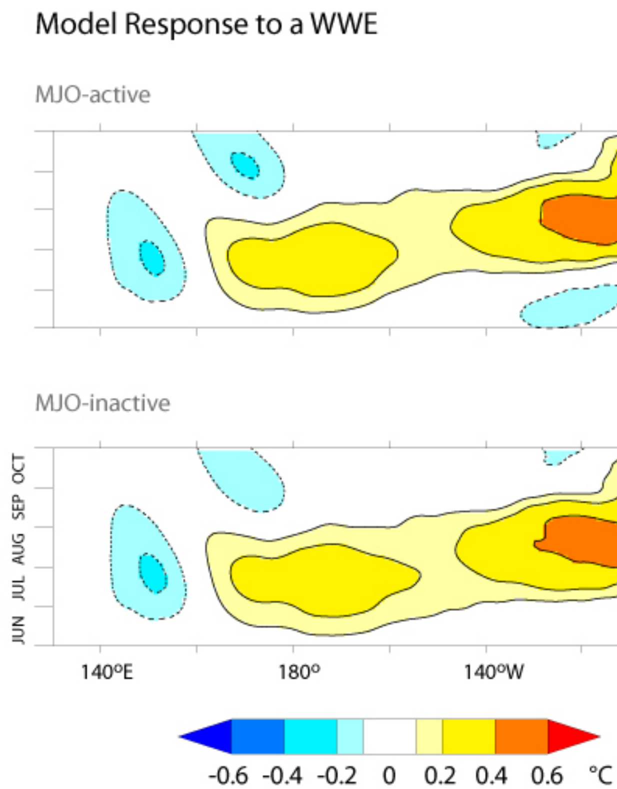


Figure 7. Model SSTA following application of a C-type WWE wind anomaly. Only WWEs that occurred in ENSO-neutral and MJO-active (-inactive) conditions were used in the composite used to drive the anomaly seen in the upper (lower) panel.

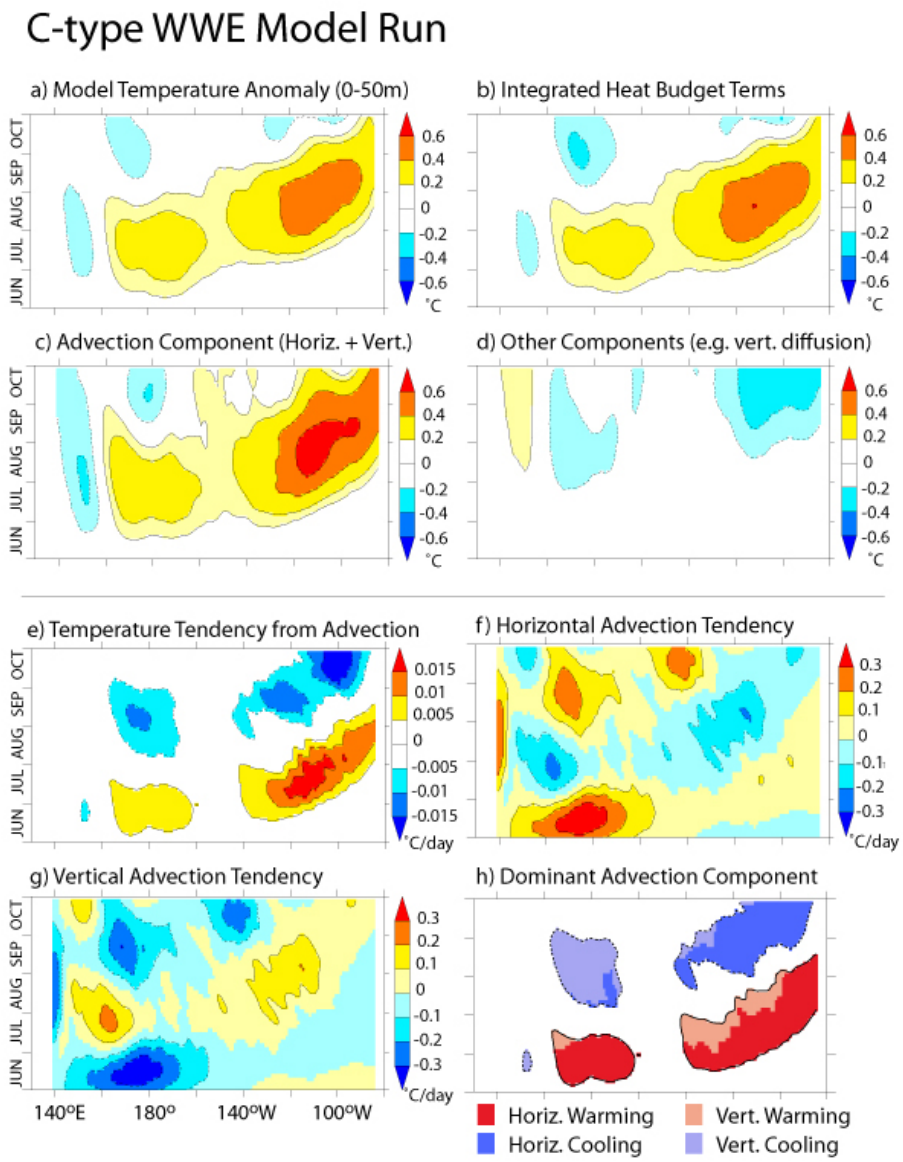
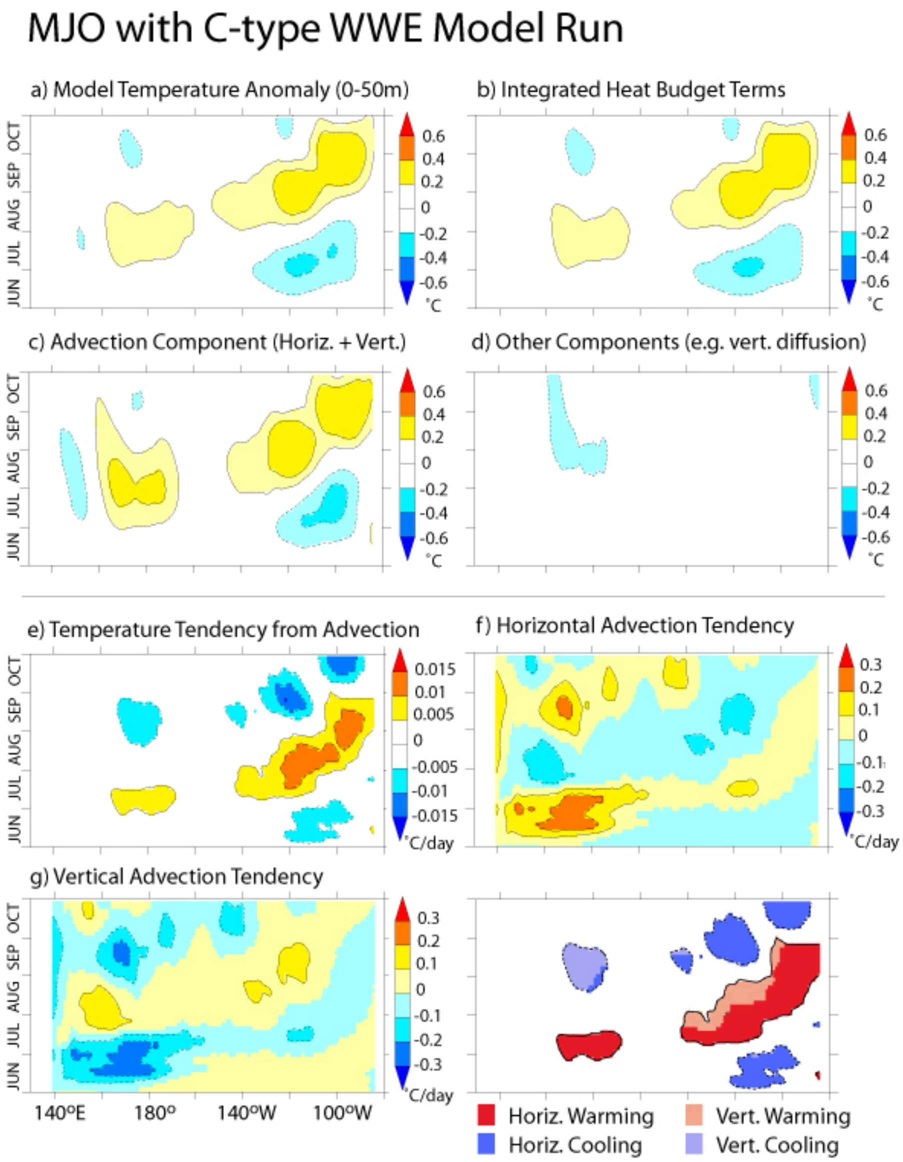


Figure 8. Near-surface ocean heat budget diagnostics from a C-type WWE model experiment; a) 0-50m average heat content anomaly, b) time-change in heat content anomaly expressed in W/m², c) sum of the heat budget terms, d) sum of just circulation-related effects, e) surface heat flux anomaly effects, f) other terms (see text). Panels (g) and (h) show the contribution of the horizontal and vertical components of the circulation anomalies to the heating/cooling anomalies shown in panel (d).



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907 Figure 9. Same as in Fig. 8, except for the MJO + WWE model experiment.

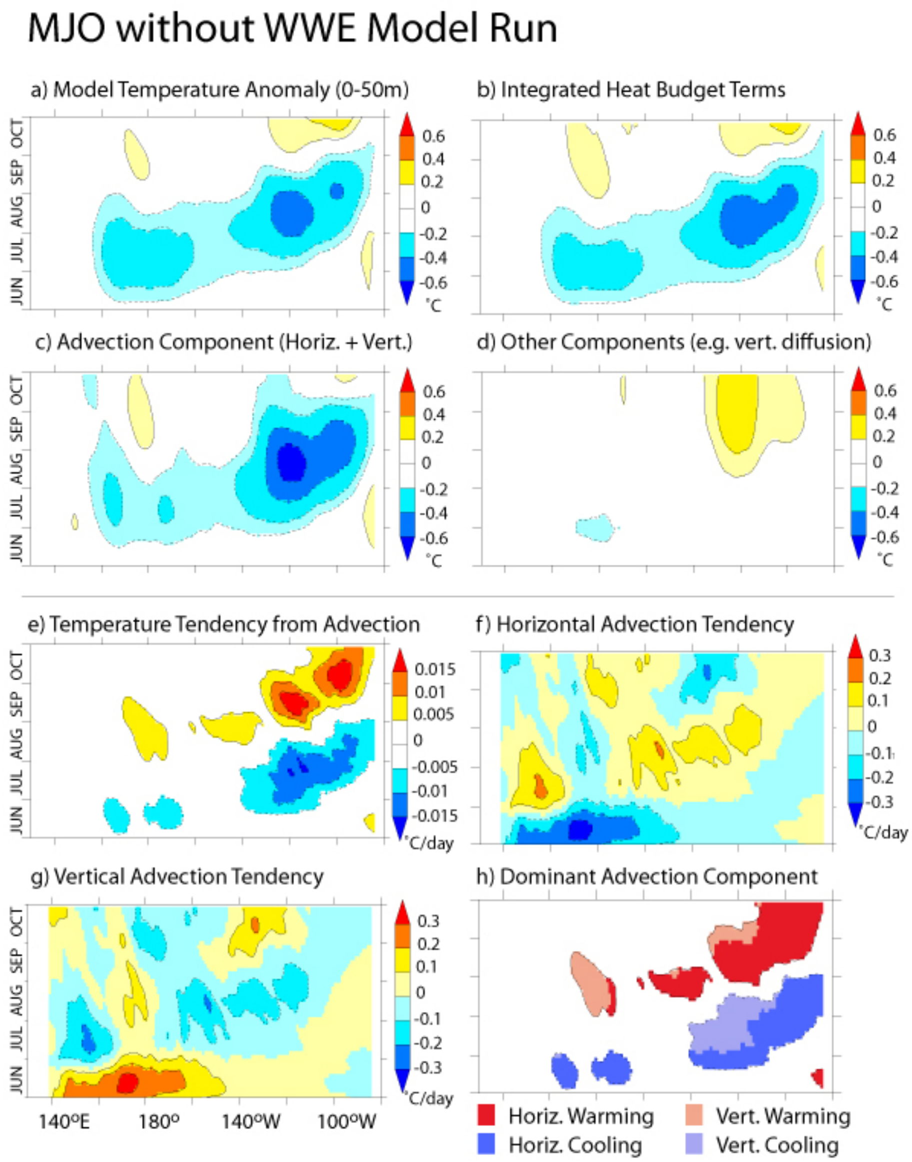

Figure 10. Same as in Fig. 8, except for the MJO-without-WWE model experiment.

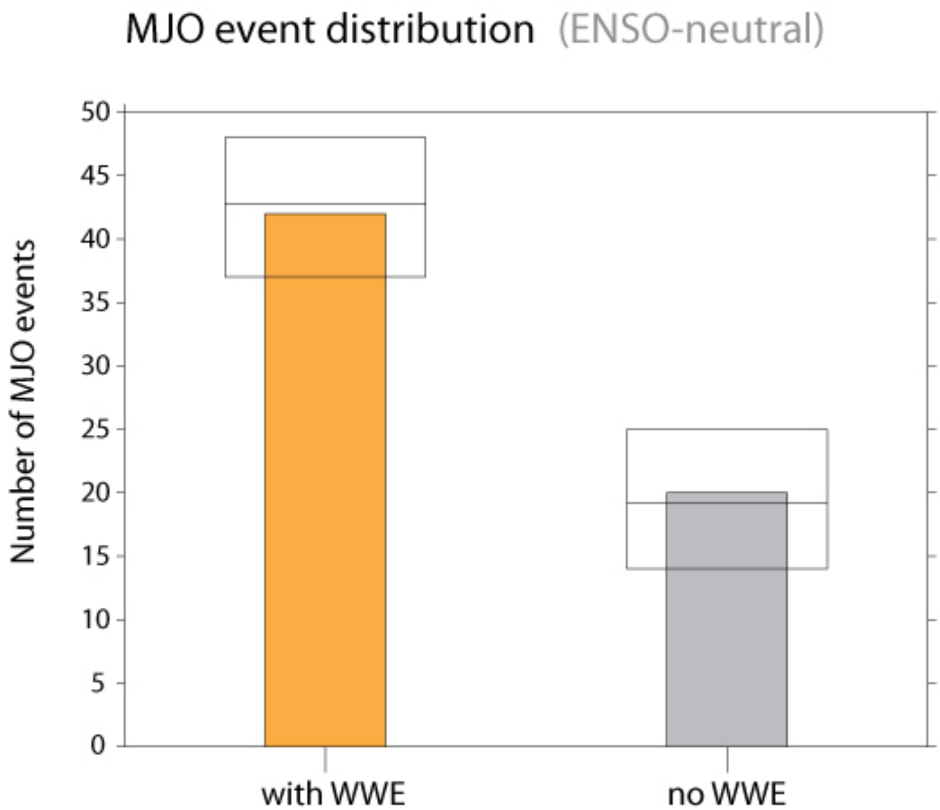

Figure 11. Number of MJO events that do and do not contain a WWE. Period 1986-2010, |NIÑO3| < 0.75°C. The top, middle and lower horizontal lines about each bar show the p=0.95, expected, and p=0.05 levels, respectively, based on a random distribution of events.

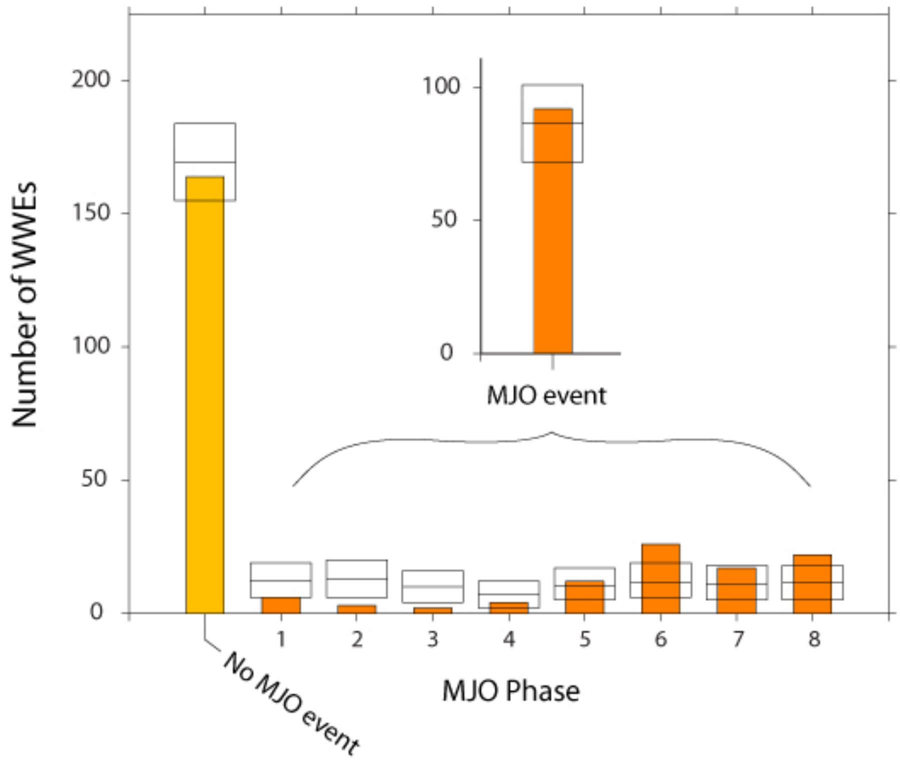

Figure 12. The numbers of WWEs that do and do not occur during an MJO event, listed by phase (based on WWE start-date) for the co-occurring case. Horizontal lines are the p=0.95, expected, and p=0.05 values.

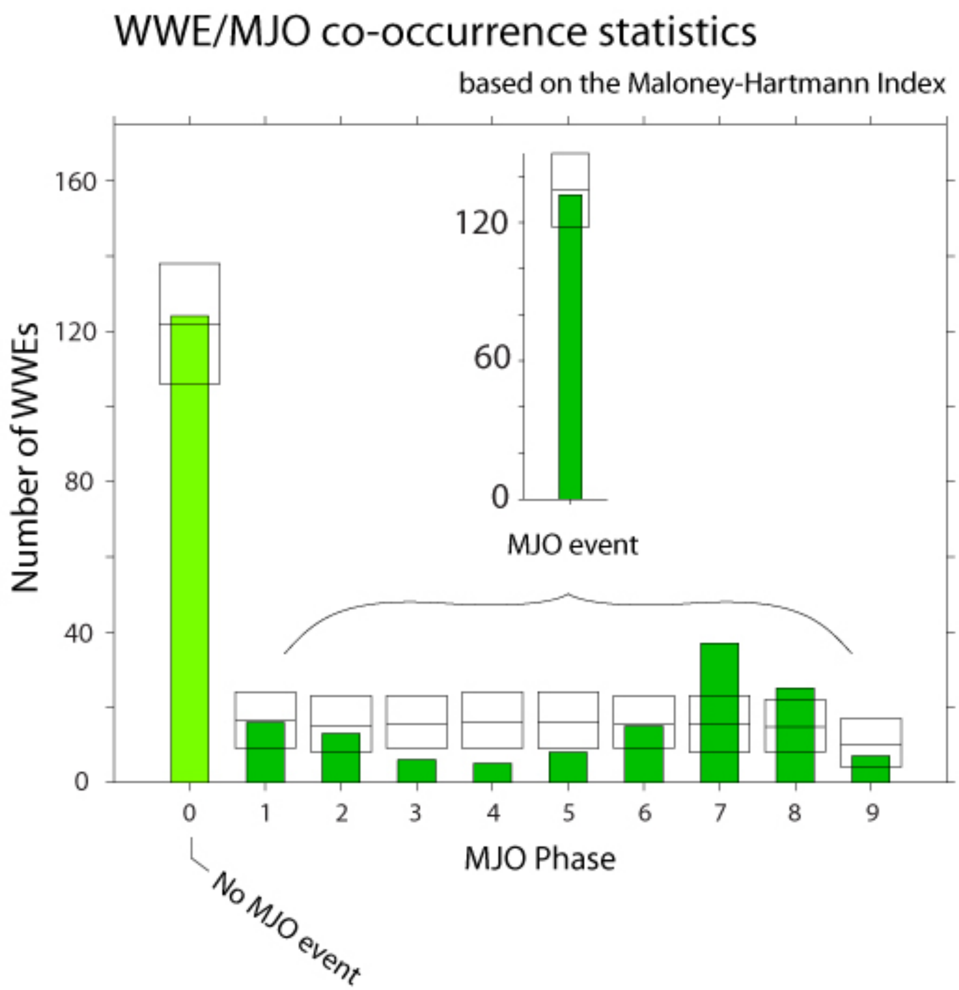

Figure 13. Same as in Fig. 12, except using the Maloney and Hartmann (1998) index for MJO event identification.

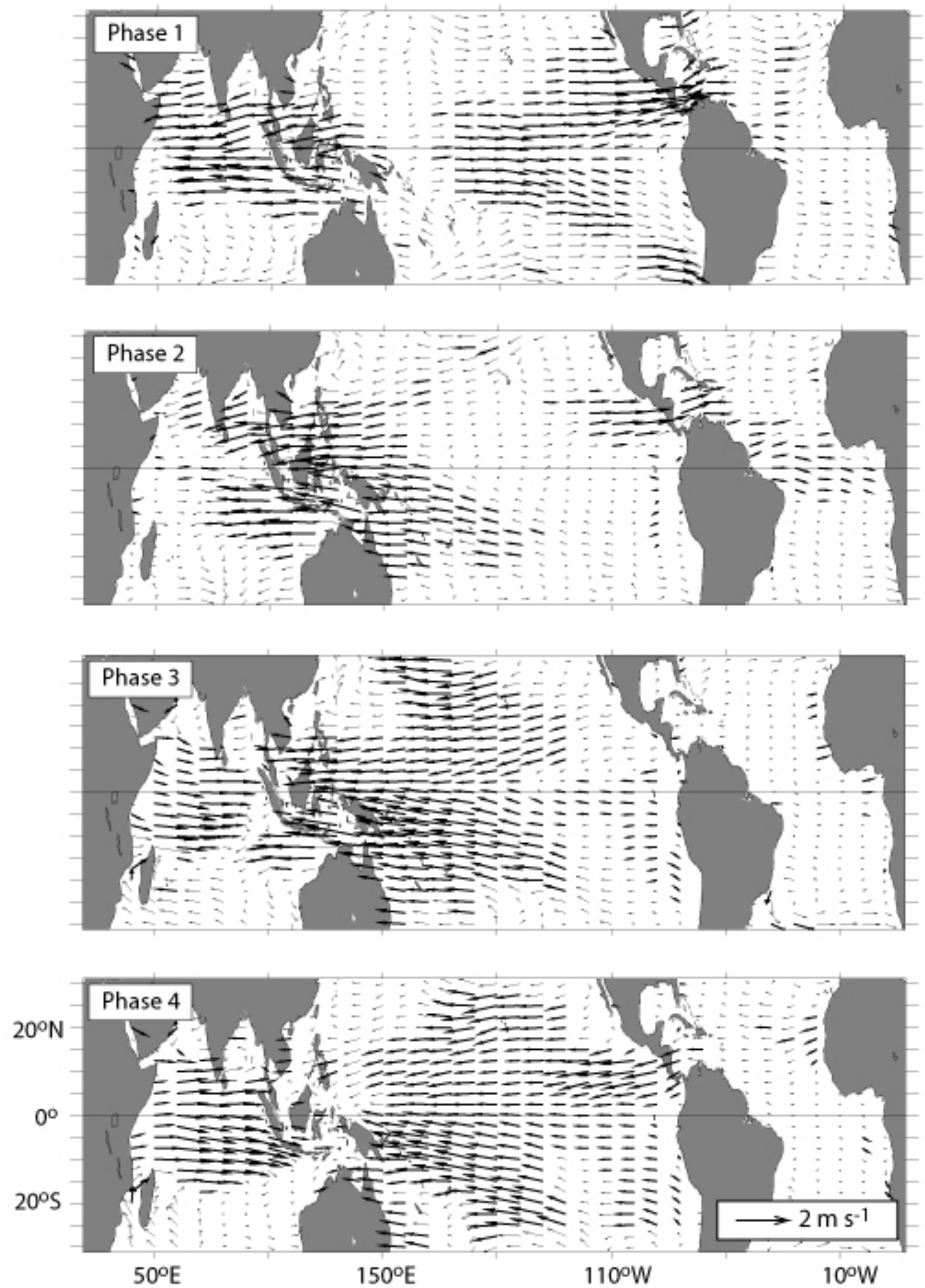

Fig. A1. Composite MJO wind anomalies. Bold arrows highlight anomalies that reach the 95% confidence level based on Monte-Carlo bootstrap methods.

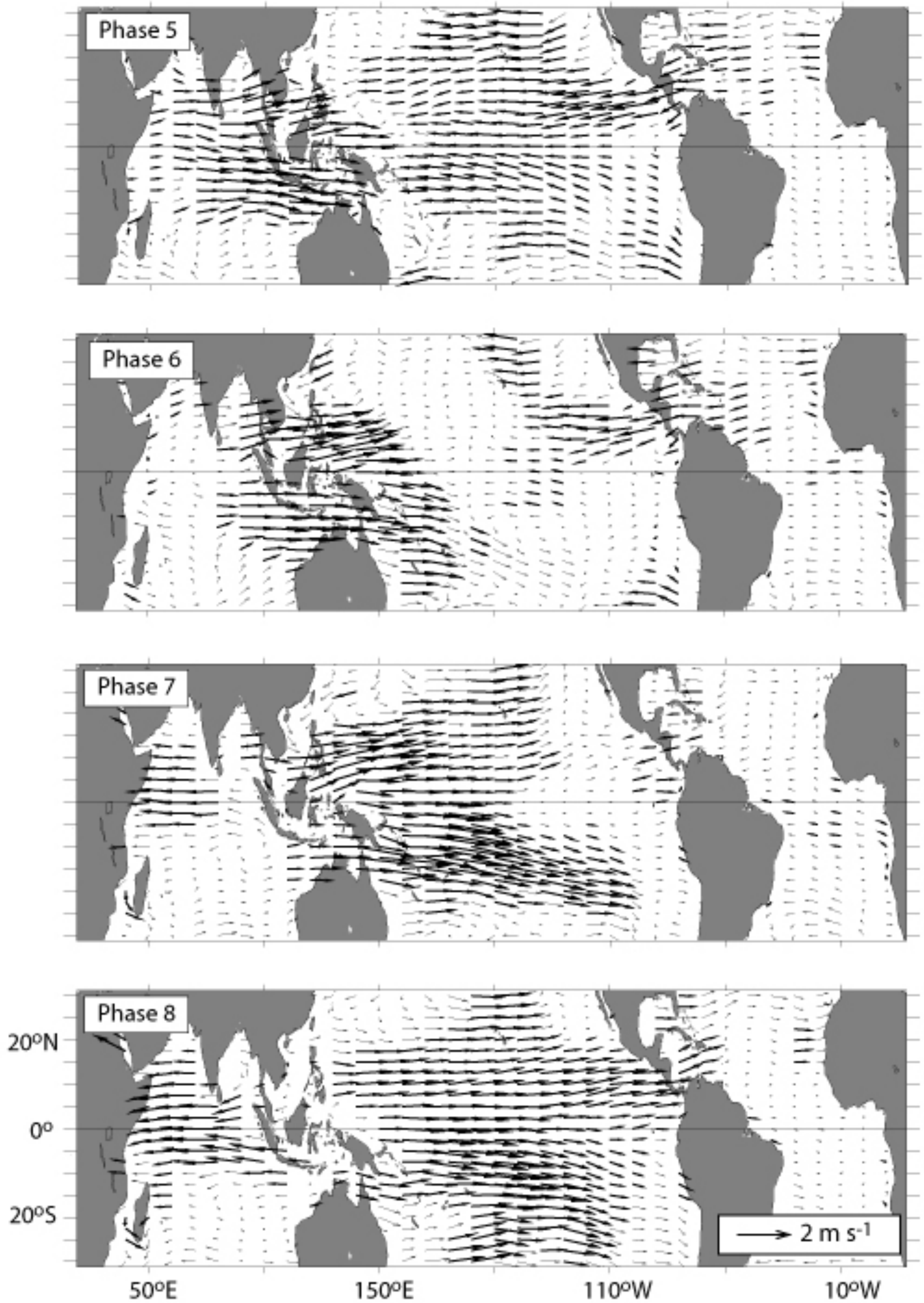

Fig. A1 continued.

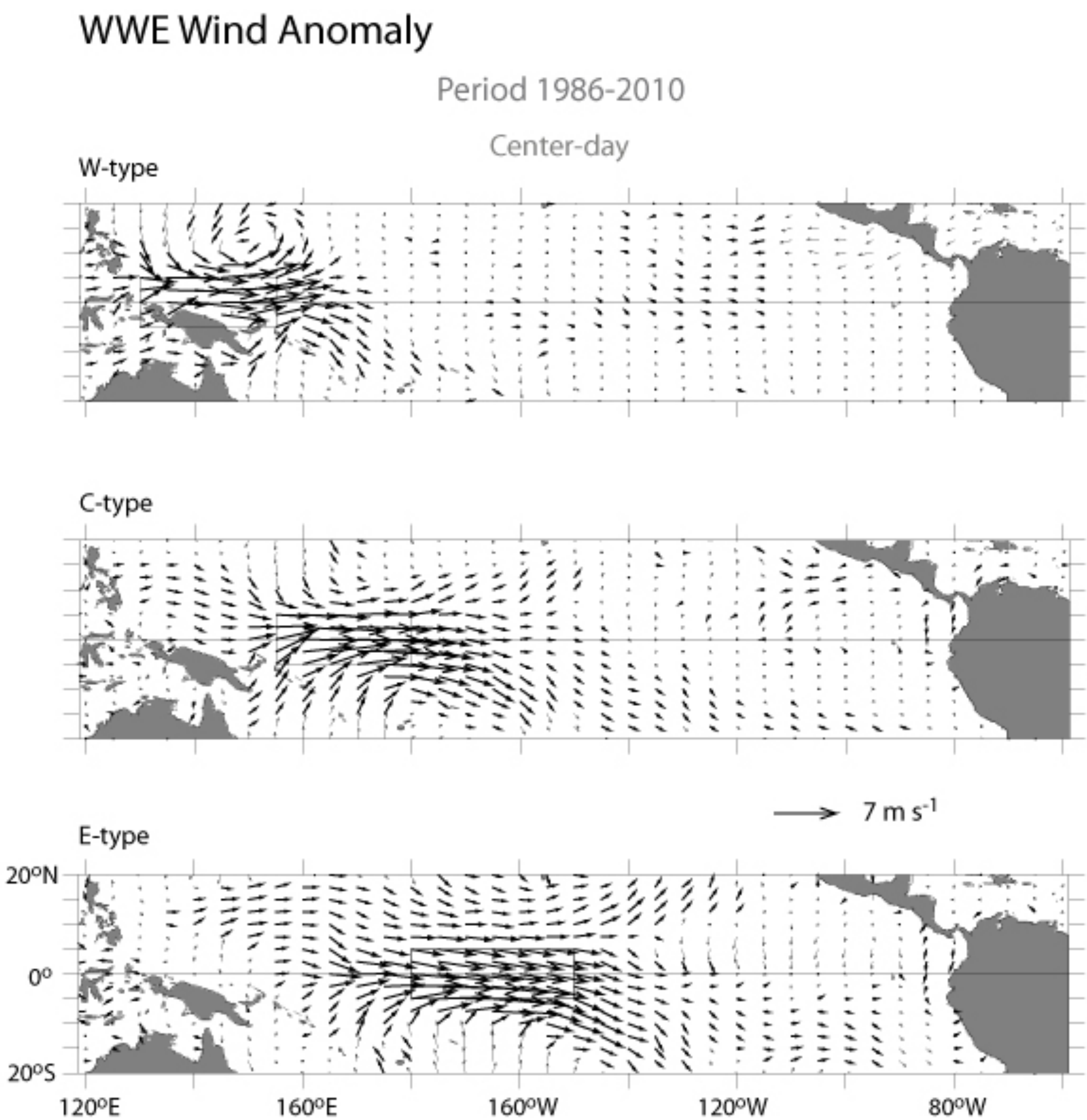

Fig. A2. Westerly wind event wind anomalies.

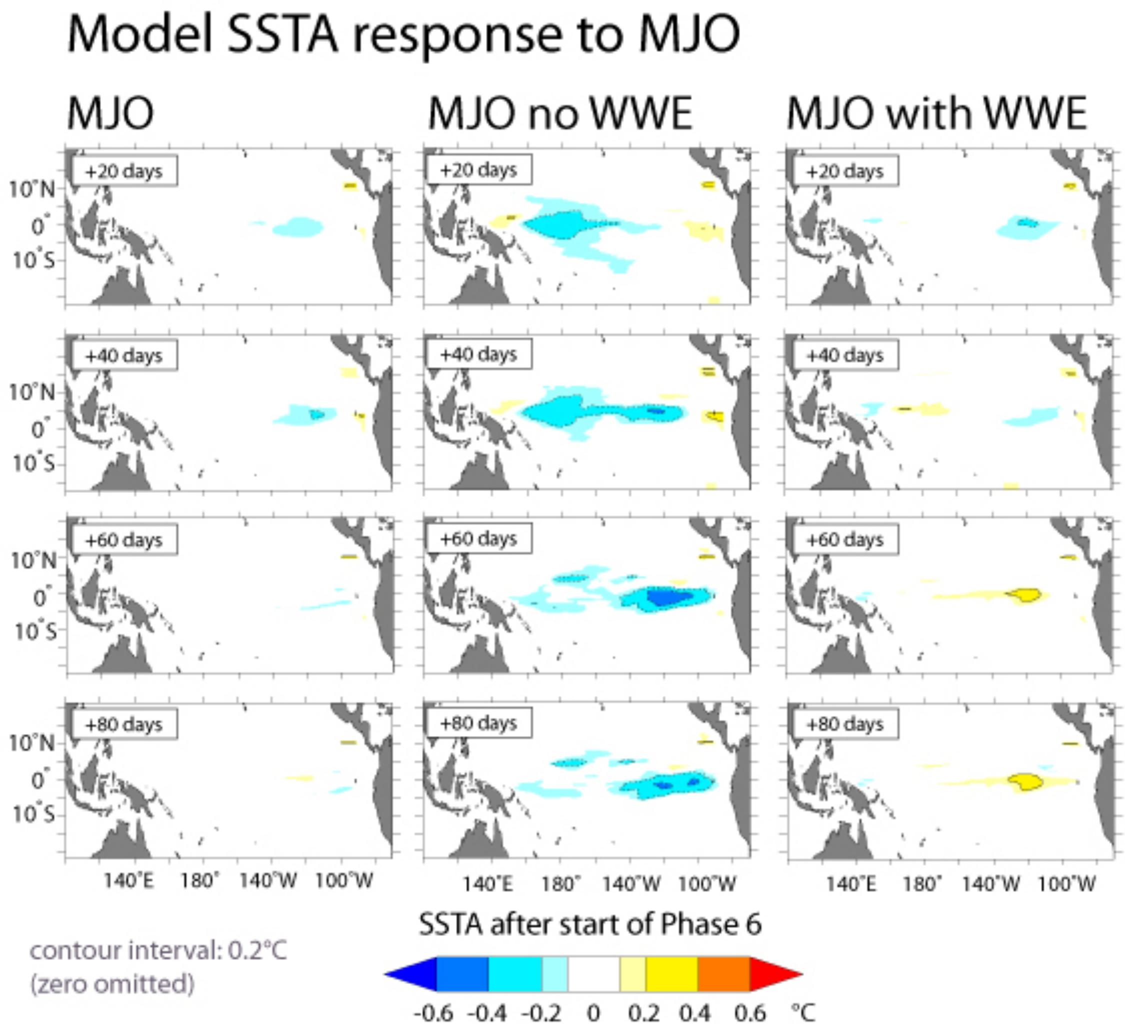

Fig. C1. Model SSTA following the application of a (variable-phase-duration) composite MJO wind stress anomaly.