Analysis of the Southward Wind Shift of ENSO in CMIP5 Models

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(Manuscript received 20 April 2016, in final form 7 December 2016)

ABSTRACT

During the mature phase of El Niño–Southern Oscillation (ENSO) events there is a southward shift of anomalous zonal winds (SWS), which has been suggested to play a role in the seasonal phase locking of ENSO. Motivated by the fact that coupled climate models tend to underestimate this feature, this study examines the representation of the SWS in phase 5 of the Coupled Model Intercomparison Project (CMIP5). It is found that most models successfully reproduce the observed SWS, although the magnitude of the zonal wind stress anomaly is underestimated. Several significant differences between the models with and without the SWS are identified including biases in the magnitude and spatial distribution of precipitation and sea surface temperature (SST) anomalies during ENSO. Multiple-linear regression analysis suggests that the climatological meridional SST gradient as well as anomalous ENSO-driven convective activity over the northwest Pacific both might play a role in controlling the SWS. While the models that capture the SWS also simulate many more strong El Niño and La Niña events peaking at the correct time of year, the overall seasonal synchronization is still underestimated in these models. This is attributed to underestimated changes in warm water volume (WWV) during moderate El Niño events so that these events display relatively poor seasonal synchronization. Thus, while the SWS is an important metric, it is ultimately the magnitude and zonal extent of the wind changes that accompany this SWS that drive the changes in WWV and prime the system for termination.

1. Introduction

One of the key features of El Niño–Southern Oscillation (ENSO) events is their tendency to mostly peak in boreal winter (i.e., November to January; Rasmusson and Carpenter 1982). It is widely understood that the interaction of ENSO with the annual cycle is the main reason for this apparent seasonal synchronization (e.g., Philander 1983; Zebiak and Cane 1987; Battisti and Hirst 1989; Xie 1995; Tziperman et al. 1997, 1998; Neelin et al. 2000; An and Wang 2000). However, the exact mechanisms are not yet fully understood, with several potential mechanisms proposed linking ENSO and the annual cycle (e.g., Philander 1983; Philander et al. 1984; Zebiak and Cane 1987; Cane et al. 1990; Jin et al. 2003; Dommenget and Yu 2016). Despite this ongoing scientific debate, the southward wind shift (SWS) has been increasingly recognized as one of the major negative feedbacks involved in ENSO seasonal phase locking and termination (Harrison and Vecchi 1999; Vecchi and Harrison 2003; Lengaigne et al. 2006; Lengaigne and Vecchi 2009; McGregor et al. 2012a, 2013, 2014; Stuecker et al. 2013; Abellán and McGregor 2016); the climate dynamics linking the SWS to seasonal phase locking will be described below.

During El Niño (La Niña) events, the associated westerly (easterly) wind anomalies are quite symmetric about the equator prior to the event peak (SON); these then move south of the equator (5°–10°S) during the
mature phase (DJF). This wind shift has been linked to the southward displacement of the Pacific’s warmest sea surface temperatures (SST) and convection during DJF (Lengaigne et al. 2006; Vecchi 2006) and the associated minimum of wind speed climatology (McGregor et al. 2012a), both of which are due to the seasonal evolution of solar radiation. Recently, the SWS has been ascribed to a climate mode generated in response to nonlinear atmospheric interaction between ENSO SST and the annual cycle of the Pacific warm pool (Stuecker et al. 2013, 2015). This nonlinear interaction produced a climate mode synchronized time evolution of the antisymmetric component of the Indo-Pacific atmospheric circulation during ENSO events (Stuecker et al. 2015). In terms of its consequences, the SWS has been shown to 1) make the thermocline depth in the eastern equatorial Pacific return to normal values (e.g., Harrison and Vecchi 1999; Vecchi and Harrison 2003, 2006; Lengaigne et al. 2006), 2) play a crucial role in the discharge process of the warm water volume (WWV) during El Niño events (McGregor et al. 2012a, 2013), and 3) transfer mass between the Northern and Southern Hemisphere during El Niño events (McGregor et al. 2014). Recently, Abellán and McGregor (2016) utilized a simple coupled model to demonstrate that the SWS during El Niño events plays a crucial role in the synchronization of the events with the annual cycle as well as a rapid termination of these events.

Apart from observational analysis (Harrison and Vecchi 1999; Vecchi and Harrison 2003), forced model studies (Spencer 2004; Vecchi and Harrison 2006; Vecchi 2006), and coupled model experiments (Vecchi et al. 2004; Lengaigne et al. 2006; Xiao and Mechoso 2009), the SWS has also been analyzed in phase 3 of the Coupled Model Intercomparison Project (CMIP3; Meehl et al. 2007). For example, Lengaigne and Vecchi (2009) considered the SWS as a precondition for the termination of El Niño owing to a shoaling of the eastern equatorial Pacific thermocline through eastward-propagating Kelvin pulses. Recently, Ren et al. (2016) found that the CMIP5 models with better performance in simulating the ENSO mode also tend to simulate a more realistic C-mode, related to the SWS as mentioned before (Stuecker et al. 2013, 2015). Additionally, the seasonal synchronization of ENSO in CMIP5 has been documented in numerous studies, showing a large model spread in this regard (Bellenger et al. 2014) and a clear dependency of this unique feature of ENSO on convective parameters (Ham et al. 2013). However, no study has yet undertaken a thorough evaluation of the representation of the SWS in state-of-the-art coupled general circulation models participating in the CMIP5 (Taylor et al. 2012); this is the overarching goal of the present study. We also investigate the dynamics underlying the SWS in CMIP5 models in addition to elucidating its link with the seasonal synchronization of ENSO events.

The rest of this paper is organized as follows. We begin in section 2 by providing a description of the datasets, CMIP5 models, and analysis method used in this study. In section 3, we evaluate how well the zonal wind stress and, in particular, the SWS are captured by CMIP5 models. An analysis of precipitation and SST anomalies during ENSO events as possible drivers of the SWS along with their mean state and multiple-linear regression analysis are then carried out in section 4. In section 5 we examine whether there is a relationship between the SWS, the peak time of these events, and the WWV changes. The final section presents a summary highlighting the main findings.

2. Models and methods

a. CMIP5 models

We focus our analyses on the historical runs by 34 CMIP5 CGCMs. A list with the official model names utilized is displayed in Fig. 1. Further information on individual models is available online (at http://www-pcmdi.llnl.gov/; Taylor et al. 2012). Although the exact duration of the simulations varies slightly from model to model, generally the historical run was carried out including solar, volcanic, and anthropogenic forcing from 1850 to 2005. Here, to avoid models with large ensemble numbers biasing the results, only one ensemble member (“r1i1p1”) run for each model is used.

The models were chosen based on the availability of model output required for this study. However, the CSIRO Mk3.6 model was excluded owing to a poor simulation of equatorial SST through ENSO phases (Brown et al. 2014; Grose et al. 2014) showing more variability in the western than in the eastern Pacific (Guilyardi et al. 2012), in stark contrast to observations.

b. Observational data

For comparison with the model results, observed atmospheric and oceanic data are used. The SST dataset is the Extended Reconstructed Sea Surface Temperature, version 3b (ERSST.v3b; Smith et al. 2008), with a 2° × 2° resolution. Both the surface wind stress and mean sea level pressure data are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) with a 1.5° × 1.5° resolution. In light of the large differences seen
across observation wind products (e.g., Wittenberg 2004; McGregor et al. 2012b). McGregor et al. (2013) utilized eight global wind products, ERA-Interim among others, finding similar spatial patterns and temporal variability for the meridional wind shift. Precipitation data are taken from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997), having a horizontal resolution of 2.5° × 2.5°.

In this study, we consider the period from 1880 to 2014 for SST and the period 1979–2014 for all other datasets, with a monthly temporal resolution adopted throughout. The anomalies for the observed variables are

![Composite mean values of zonal wind stress anomalies during (a),(d),(g) strong El Niño, (b),(e),(h) moderate El Niño, and (c),(f),(i) La Niña for the period September0–February1, where 0 means the year during which an event develops and 1 means the decaying year, for (a)–(c) observations, (d)–(f) ensemble mean, and (g)–(i) all CMIP5 models. Note the different color bars for the observations and CMIP5 models. Taylor diagrams are obtained by calculating the standard deviation and correlation between each model and observations for the whole domain shown in the left panels.](image)

Fig. 1.
defined as the deviations from the 1979–2014 climatological mean.

c. Methodology

Anomalies of all CMIP5 fields are calculated by removing the long-term monthly climatology over the entire period available for each model, whereas the period used to calculate the observed long-term monthly climatology is as discussed above in section 2b. Prior to the calculations, a 3-month binomial filter was applied to all wind stress data (including both the observed and CMIP5 modeled) in order to reduce month-to-month noise, as described in Deser et al. (2012). Both model data and observations were linearly detrended to approximately account for model drift and the impacts of global warming, to first order. Model outputs were examined at native grid resolution and then later interpolated to the same grid as the observations, to facilitate comparison with the measurement record and assessment of the multimodel means.

It has been shown that the dynamics of extreme El Niño events are different from moderate events (e.g., Dommenget et al. 2013; Santoso et al. 2013; Cai et al. 2014, 2015; Capotondi et al. 2015; Takahashi and Dewitte 2015). Therefore, here we classify El Niño events according to the magnitude of SST anomalies within the region 5°S–5°N, 170°–120°W (hereafter the Niño-3.4 index), while La Niña events only have the one category. Specifically, 1) strong El Niño events are identified when the Niño-3.4 index exceeds 1.5°C, 2) moderate El Niño events when the index is greater than 0.5°C but less than or equal to 1.5°C, and 3) La Niña events when the index is less than −0.5°C, for at least 5 consecutive months in all three cases. Following this criterion, we find in the observations two strong El Niño events (1982/83 and 1997/98), seven moderate El Niño events (1987/88, 1991/92, 1994/95, 2002/03, 2004/05, 2006/07, and 2009/10), and eight La Niña events (1984/85, 1988/89, 1995/96, 1999/2000, 2000/01, 2007/08, 2010/11, and 2011/12) during the period 1979–2014. It is worth pointing out that there are four CMIP5 models (GISS-E2-R-CC, INM-CM4.0, MIROC-ESM, and MRI-CGCM3) that are not capable of simulating strong El Niño events, according to our definition. We note that as ENSO events typically peak near the end of the calendar year, here we composite during DJF regardless of event peak.

3. Wind stress during ENSO

Ocean surface wind stress (hereafter wind stress) is an important variable in the coupled system as it indicates the exchange of momentum between the ocean and atmosphere (Lee et al. 2013). Furthermore, the spatial structure of anomalies during ENSO is considered an important factor in setting the ENSO time scale (e.g., Kirtman 1997; Wang et al. 1999; An and Wang 2000; Capotondi et al. 2006; Neale et al. 2008; Kug et al. 2009). Figures 1a–c show the composite of zonal wind stress anomalies for the period September (0) to February (1) for observed strong El Niño, moderate El Niño, and La Niña events, respectively. The spatial pattern of the observed zonal wind stress anomalies displays westerlies (easterlies) during El Niño (La Niña) with maximum Pacific anomaly located between the equator and 5°S. However, two distinct features between the strong El Niño events and the other two types of ENSO events can be clearly seen: 1) different magnitude (i.e., twice as strong for strong El Niño events) and 2) westward shift of maximum zonal wind stress anomalies during La Niña and moderate El Niño events (by about 30° compared to the strong El Niño pattern), which are almost mirror images. Previous studies have demonstrated that these wind stress differences (i.e., magnitude and location) have been associated with the nonlinear characteristics of the atmospheric response to the SST anomalies of the opposite sign (i.e., via atmospheric convection; Kang and Kug 2002; Ohba and Ueda 2009; Frauen and Dommenget 2010).

Although the zonal distribution of CMIP5 ensemble mean zonal wind stress anomalies are qualitatively similar to those observed, some differences can be seen (Figs. 1a–f): (i) the magnitude of the CMIP5 ensemble mean anomalous wind stress for each ENSO event type is much weaker (up to 50%–60%) than the observations for its corresponding event type, which is consistent with the results of Bellenger et al. (2014); (ii) the multimodel mean CMIP5 simulated equatorial winds are not as broad meridionally as those observed (i.e., the CMIP5 ensemble mean winds only extend to approximately 3°N and 7°S; cf. Figs. 1d–f), which can impact the period of ENSO (Capotondi et al. 2006); and (iii) the anomalous wind stresses have a larger longitudinal span than the observations, consistent with the earlier study of Lee et al. (2013).

To further assess the skill of the CMIP5 ensemble set in simulating the observed spatial pattern of anomalies of zonal wind stress during ENSO events, we present Taylor diagrams (Taylor 2001) in Figs. 1g–i for the three types of ENSO events. Generally speaking, the CMIP5 models produce reasonable correlations when compared with the observations, with average spatial correlation values of 0.58, 0.55, and 0.59 for strong El Niño, moderate El Niño, and La Niña events, respectively. In regard to the standard deviation of zonal wind stress patterns, most of the CMIP5 models have less variance (11.0, 4.9, and 4.8 mPa as mean values) than that seen in the observations (16.8, 6.3, and 6.2 mPa for strong
El Niño, moderate El Niño, and La Niña, respectively). The fact that the magnitude of simulated zonal wind stress is weaker than observed (Fig. 1), with a reduced meridional width, might explain the low standard deviation of the associated composite spatial maps.

a. The southward wind shift

As mentioned in the introduction, the SWS refers to a meridional movement of the anomalous wind stresses during the ENSO event mature phase (i.e., boreal winter). In particular, the maximum of these anomalies is located at (or slightly north of) the equator during August–October (ASO), while the magnitude of the wind stress is increased (decreased) south (north) of the equator during November–January (NDJ), such that the maximum zonal wind stress occurs south of the equator during February–April (FMA; e.g., Harrison and Vecchi 1999; McGregor et al. 2013). Here we define the SWS as the difference in latitude of the maximum zonal wind stress anomalies between ASO and FMA, averaged over 160°E–120°W. It is worth emphasizing that other factors, such as the strength and meridional width of the anomalies, also impact the oceanic response to the SWS. However, none of these changes are of interest if the model does not first produce the SWS. Thus, here we have chosen to focus our SWS definition on changes in the latitude of the wind stress anomalies, but we also note that the oceanic impact of the SWS is discussed in section 5 of this study. The magnitude of the observed SWS is 9.0°, 6.0°, and 7.5° for strong El Niño, moderate El Niño, and La Niña events, respectively.

Figure 2 displays the latitude of the maximum westerly (easterly) anomalies from August to April during El Niño (La Niña) years averaged zonally over the western and central Pacific. We note that these latitudes are calculated based on the composite mean zonal wind stress for each model. Here and in the rest of the paper we divide the CMIP5 models into two categories: models with SWS and those without SWS. This classification is based on the ability of each model to realistically reproduce an SWS during the three types of ENSO events, with the magnitude of the shift required to be at least 66.6% of the observed SWS.

The majority of the models simulate realistic SWS during at least one of the three types of defined ENSO events. In fact, two-thirds of the CMIP5 models analyzed (22 out of 34) can reproduce the SWS for all three types of events analyzed. It is also clear that the multimodel ensemble mean of models with SWS (MME with SWS) is comparable with observations (Figs. 2a–c). It is interesting to note that MME with SWS indicates stronger SWS for strong El Niño events (reaching the maximum of westerly anomalies up to 6°S in March) than that for moderate El Niño or La Niña (located at 4°S in the same month), which is also seen in observations. There are 4 (out of 30) models that do not capture the SWS during strong El Niño (Fig. 2d), while there are 6 and 4 (out of 34) models that do not reproduce the SWS during moderate El Niño and La Niña, respectively (Figs. 2e,f). The multimodel ensemble average of these models (i.e., MME without SWS) exhibit latitude of maximum zonal wind stress roughly constant (and south of the equator) throughout the 9-month period. It is also worth mentioning that two models (IPSL-CM5A-LR and IPSL-CM5A-MR) are not able to simulate the SWS for any type of ENSO event. The study of Bellenger et al. (2014) analyzes various other ENSO metrics and also concludes that the ENSO in these last two models exhibits poor agreement with observations.

b. SWS spatial characteristics

To highlight the SWS we present composite maps of the zonal wind stress and sea level pressure (SLP) anomaly difference between FMA and ASO for the observations and the CMIP5 models with and without SWS and for the three types of ENSO events (Fig. 3). The observational differences during strong El Niño events show several clear structures over the tropics: 1) easterly differences in the western Pacific north of the equator, 2) westerly differences over the central Pacific south of the equator, and 3) high positive anomalous SLP observed over the northwestern Pacific representing a large-scale low-level anticyclone (Fig. 3a). All of these features are consistent with the representation of this southward wind shift by an empirical orthogonal function (EOF) analysis (McGregor et al. 2013) and the C-mode, which emerges from the seasonal modulation of ENSO-related atmospheric anomalies (Stuecker et al. 2013). It is noted that the high SLP anomalies in the northwest are generally referred to as the Philippine Sea anticyclone (e.g., Harrison and Larkin 1996; Wang et al. 1999, 2000; Wang and Zhang 2002; Li and Wang 2005). Values in the center of the Philippine Sea anticyclone during strong El Niño years (~3 hPa), as shown in Fig. 3a, are larger than the amplitude of the local annual variation (~2 hPa) (Wang and Zhang 2002).

The observed zonal wind stress differences for moderate El Niño show a similar dipole structure to those for strong El Niño, although both easterly and westerly differences in the tropical Pacific are shifted westward, and their magnitudes are much weaker (Fig. 3b). Furthermore, the longitudinal offset of the winds north and south of the equator is reduced. Not surprisingly, the development of the Philippine Sea anticyclone is also more modest because of its link to the El Niño amplitude (Wang and Zhang 2002; Stuecker et al. 2015).
In contrast, the La Niña phase during FMA–ASO leads to an anomalous cyclone developing over the Philippine Sea reversing both its sign and the pattern of zonal wind anomalies (i.e., westerly seasonal difference north of the equator and easterly south of the equator; Fig. 3c). Unlike warm events, these two regions of opposite zonal wind stress anomalies north and south of the equator are centered at roughly the same longitude. Further to this, their magnitudes are weaker than those for moderate El Niño events.

In qualitative agreement with observations, models with SWS display anomaly differences between FMA and ASO with patterns similar to those observed (Figs. 3d–f). This includes positive (negative) anomalous SLP over the Philippine Sea region during El Niño (La Niña) events and pronounced differences in zonal wind stresses in the western Pacific north of the equator and central Pacific south of the equator. However, the seasonal differences of zonal wind stress anomalies are underestimated among models, especially for strong El Niño events. The anomalous SLP in the Philippine anticyclone region is also roughly half the magnitude observed. Another obvious difference between the observations and the CMIP5 models with SWS is the lack of simulated zonal offset of the zonal winds about the equator for strong El Niño. In particular, the positive zonal wind difference south of the equator is underestimated among models, especially for strong El Niño events.

Fig. 2. Latitude of anomalous zonal wind stress maximum averaged over 160°E–120°W during ENSO events, for the period August–April. A 3-month running mean is applied; for instance, the value for August is the average of July, August, and September and so forth. Simulations are divided into models (a)–(c) with SWS and (d)–(f) without SWS for (a),(d) strong El Niño, (b),(e) moderate El Niño, and (c),(f) La Niña. See section 3a for SWS classification.
equator is not offset to the east of the negative zonal wind difference above the equator as seen in observations. Even though most models without an SWS (according to the criterion we adopt) can simulate an SWS to some extent, albeit with much weaker magnitude, the meridional movement tends to be displaced too far to the west compared to the observations (Figs. 3g–i). Consequently, the Philippine Sea anticyclone (cyclone) is not as well developed during the simulated El Niño (La Niña). The westward extension of ENSO-related zonal wind stress anomalies found in the CMIP5 models, which is more pronounced in models without an SWS, is a common failure for most CGCMs (Kirtman et al. 2002; Zhang and Sun 2014).

4. Possible drivers of the SWS

a. The role of anomalies

It is generally accepted that the anomalous SST during ENSO events is intimately linked with rainfall and wind stress anomalies (e.g., Bjerknes 1969; Ropelewski and Halpert 1987; Philander 1990). Thus, in this section we explore both qualitatively and quantitatively (using linear regression) the relationship between the representation of SWS, the details of the SST anomalies, the accompanying precipitation, and their climatology during boreal winter.

1) SST ANOMALIES

It is well known that El Niño (La Niña) events are characterized by anomalously warm (cold) SST over the central-eastern equatorial Pacific (Figs. 4a–c). In particular, during strong El Niño events, the maximum SST anomalies are situated in the eastern equatorial Pacific (Fig. 4a), where the cold tongue is located (Larkin and Harrison 2005; Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009; Kim et al. 2009; Holland 2009). However, during moderate El Niño events the maximum SST anomalies are weaker and shifted to the west, while La Niña events generally mirror the moderate El Niño (Figs. 4b,c). This shift to the west of the maximum SST anomalies with weaker values off the South American coast for moderate El Niño is consistent with aspects of ENSO diversity described in the literature (Takahashi et al. 2011; Capotondi et al. 2015).

FIG. 3. Zonal wind stress anomaly composites during FMA season minus that during ASO season (shading) and SLP anomaly (contours) for (a),(d),(g) strong El Niño, (b),(e),(h) moderate El Niño, and (c),(f),(i) La Niña for (a)–(c) observation, (d)–(f) models with SWS, and (g)–(i) models without SWS. Note that negative contours are dashed; units for both variables are in Pa and that we employ different color bars to better highlight all events more clearly. The numbers in each panel indicate the number of the events falling within that category.
Both groups of CMIP5 models broadly reproduce SST anomaly patterns that are overall consistent with those observed, including most models producing La Niña and moderate El Niño events as approximate mirror images of each other (Figs. 4e,f). However, it is noted that the models have been shown to underrepresent the observed ENSO diversity (e.g., Capotondi and Wittenberg 2013), and here we highlight several other notable differences. First, in contrast to the observations, models that reproduce the SWS exhibit no significant differences in the location of SST anomalies between strong and moderate El Niño (Figs. 4d,e). These models also display a westward shift of the anomalous SST values during extreme El Niño events compared to observations. For instance, the anomalous 0.5°C isotherm is shifted around 10° longitude when compared to that observed. Models without an SWS tend to underestimate the magnitude of the anomalous values of SST for La Niña and strong El Niño, whereas the amplitude is larger for moderate El Niño (Figs. 4g–i).

Here we calculate and display the ensemble mean SST anomaly differences between models with and without an SWS in an attempt to better understand the cause of the SWS (Figs. 4j,k). The differences between these two types of models (with and without the SWS) show warmer conditions over the eastern and colder over the western equatorial Pacific for El Niño events, although the eastern Pacific difference is larger for the strong events and the western Pacific difference is larger for moderate events. We also find that the maximum event

![Fig. 4. SST anomalies in DJF during (a),(d),(g),(j) strong El Niño, (b),(e),(h),(k) moderate El Niño, and (c),(f),(i),(l) La Niña for (a)–(c) observations, (d)–(f) models with SWS, (g)–(i) models without SWS, and (j)–(l) the difference between models with and without SWS. Note the different color scales.](image-url)
Table 1. Coefficients of determination $R^2$ and correlation coefficient $r$ (shown in parentheses) between possible drivers of the SWS and the SWS index (defined in section 3a). Note that bold values indicate that the correlation is significant at the 95% confidence level. The meridional gradients are defined as the average over the equatorial region ($5^\circ$–$4^\circ$N, $120^\circ$E–$160^\circ$W) minus the average over the north off-equatorial region ($5^\circ$–$12^\circ$N, $140^\circ$E–$160^\circ$W). For climatological predictors, we focus on the DJF season, when the anomalous zonal winds are migrating southward. The number of degrees of freedom is 28 for strong El Niño and 32 for the other events.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Strong El Niño</th>
<th>Moderate El Niño</th>
<th>La Niña</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR$_{clim}$</td>
<td>Meridional gradient of climatological precipitation during DJF</td>
<td>0.160 (0.40)</td>
<td>0.396 (0.63)</td>
<td>0.262 (0.51)</td>
</tr>
<tr>
<td>SST$_{clim}$</td>
<td>Meridional gradient of climatological SST during DJF</td>
<td>0.293 (0.54)</td>
<td>0.428 (0.65)</td>
<td>0.397 (0.63)</td>
</tr>
<tr>
<td>TAUX$_{clim}$</td>
<td>Meridional gradient of climatological zonal wind stress during DJF</td>
<td>0.160 (0.40)</td>
<td>0.247 (0.50)</td>
<td>0.242 (0.49)</td>
</tr>
<tr>
<td>PR$_{anom}$</td>
<td>Precipitation anomaly in DJF averaged over 0°–10°N, 120°E–160°E during ENSO</td>
<td>0.294 (0.54)</td>
<td>0.518 (0.72)</td>
<td>0.333 (0.58)</td>
</tr>
<tr>
<td>SST$_{anom}$</td>
<td>Equatorial ($5^\circ$–$5^\circ$N) maximum SST anomaly in DJF during ENSO</td>
<td>0.137 (0.37)</td>
<td>0.026 (0.16)</td>
<td>0.248 (0.50)</td>
</tr>
<tr>
<td>TAUX$_{anom}$</td>
<td>Maximum zonal wind stress anomaly between 10°S and 10°N averaged over August–April and 160°E–120°W during ENSO</td>
<td>0.199 (0.45)</td>
<td>0.352 (0.59)</td>
<td>0.190 (0.44)</td>
</tr>
<tr>
<td>CT</td>
<td>Annual mean climatology of SST over 2°S–2°N, 150°E–110°W (cold tongue)</td>
<td>0.081 (0.29)</td>
<td>0.141 (0.38)</td>
<td>0.099 (0.32)</td>
</tr>
<tr>
<td>LON$_{55}$</td>
<td>Longitude of ±0.5°C SST anomaly over the equator in DJF during ENSO years</td>
<td>0.097 (0.31)</td>
<td>0.138 (0.37)</td>
<td>0.068 (0.26)</td>
</tr>
<tr>
<td>ZRes</td>
<td>Zonal resolution of the atmosphere</td>
<td>0.113 (0.34)</td>
<td>0.068 (0.26)</td>
<td>0.098 (0.31)</td>
</tr>
<tr>
<td>MRes</td>
<td>Meridional resolution of the atmosphere</td>
<td>0.054 (0.23)</td>
<td>0.119 (0.35)</td>
<td>0.021 (0.15)</td>
</tr>
</tbody>
</table>

magnitude, identified with each model’s SST anomaly in DJF, is statistically significantly related to the magnitude of the SWS during La Niña and strong El Niño events (Table 1). If we instead classify the event magnitude with the magnitude of the wind stress response (rather than SST magnitude) we find that the relationship between the event magnitude and the SWS decreases (increases) for La Niña (strong El Niño) (Table 1). We also find that the erroneous westward displacement of western edge of SST anomalies during extreme El Niño events is much more pronounced in models without an SWS, and it is also seen during moderate El Niño events in these models. However, the relationship between the extent of the westward shift of the SST anomaly edge and the magnitude of the SWS is only statistically significant for moderate El Niño events (Table 1). The shift toward the west of the SST anomaly edge has been related to the cold tongue bias, which is one of the long-standing problems among climate models (Kirtman et al. 2002; Capotondi et al. 2006) and still remains an issue in CMIP5 models (Brown et al. 2014; Kug et al. 2012; Capotondi and Wittenberg 2013; Ham et al. 2012; Ham and Kug 2015). Consistent with the westward bias, we also find a linear significant relationship between the SST bias in the equatorial Pacific cold tongue region ($2^\circ$–$2^\circ$N, $160^\circ$E–$90^\circ$W; Li et al. 2016) and the SWS magnitude for moderate El Niño events (Table 1).

2) Precipitation Anomalies

During strong El Niño events, the warm SST anomalies over the equatorial central and eastern Pacific lead to the equatorward displacement of the intertropical convergence zone and South Pacific convergence zone resulting in positive precipitation anomalies over this region (Fig. 5a). In contrast, negative precipitation anomalies are robust to the north, south, and west of this enhanced precipitation (Fig. 5a), showing that this is more a redistribution than an increase (Choi et al. 2015). This redistribution of precipitation during strong El Niño events is also seen in the CMIP5 models; however, the magnitude of the model anomalies is much weaker, and this bias is more pronounced in models without the SWS. In fact, there is a statistically significant relationship between precipitation anomalies in the northwestern Pacific and the magnitude of the SWS (see yellow box in Fig. 5; Table 1). Consistent with the westward shift of the SST anomaly edge seen in both model groups (Fig. 4), the enhanced equatorial precipitation during strong El Niño events is also shifted to the west relative to observations (Figs. 5a–c) (Misra et al. 2007; Cai et al. 2012; Kug et al. 2012).

A similar pattern of precipitation is observed for moderate El Niño events (i.e., negative anomalous values of rainfall over the western tropical Pacific and positive over the central Pacific) (Fig. 5e), although the anomaly magnitude is around half that seen for strong El Niño events and no anomalies are observed over the eastern equatorial Pacific for moderate El Niño events consistent with the study of Cai et al. (2014). As for strong El Niño events, the models tend to simulate excessive precipitation anomalies over the western Pacific warm pool region, which is likely due to the westward shift of SST anomalies as this bias is more marked in
models without an SWS (Figs. 5f,g). As a consequence, the difference map exhibits more (less) precipitation anomalies over the central-west (far west) equatorial Pacific (Fig. 5h). Again the northwestern Pacific changes are so robust that a statistically significant relationship between precipitation anomalies in the northwestern Pacific and the magnitude of the SWS also exists for moderate El Niño events (Table 1).

For observed La Niña events, there is a marked similarity with moderate observed El Niño events (Figs. 5e,i), although with opposite anomaly patterns, as expected [i.e., drier (wetter) conditions than normal over the central/western (far west) equatorial Pacific]. As before, the CMIP5 models underestimate the magnitude of the anomalous rainfall during La Niña compared to observations, particularly those without an SWS (Figs. 5j,k). Focusing again on precipitation anomalies in the northwestern Pacific, a statistically significant relationship is found between the anomaly magnitude and the magnitude of the SWS during La Niña events (Table 1).

b. The role of the mean state

It has been suggested that climatological biases affect the fidelity of the simulation of ENSO in climate models (Wang and An 2002; Guilyardi 2006; Sun et al. 2009; Bellenger et al. 2014). Here, we analyze the climatological SST, precipitation, and wind stress during DJF in the tropical Pacific to further examine if mean state biases might influence the ability of CMIP5 models to simulate the SWS during ENSO events. We chose to
focus on the DJF period as this is when the surface winds are migrating southward, but we also note that the differences between the CMIP5 with SWS and CMIP5 without SWS are very similar regardless of whether MAM or ASO was selected (not shown).

The tropical Pacific mean state is characterized by relatively cold SST in a band centered on the equator in the central and eastern Pacific, and the warmest temperatures in the west (Fig. 6a). These two regions are commonly referred to as the cold tongue and warm pool, respectively. The climatological precipitation during DJF exhibits two bands of heavy precipitation: the first extending across the central-eastern Pacific (i.e., the ITCZ) and the second extending southeast from near New Guinea to the southeastern Pacific (i.e., the SPCZ), with highest rainfall in the SPCZ (Fig. 6a). Consequently, minimum wind stress is observed in the SPCZ region, and the strongest easterly anomalies are found north and south of the ITCZ, converging in this area (total winds not shown).

To first order, the models (both with and without the SWS) appear to do a reasonable job capturing the main features of the observed spatial patterns of SST and precipitation described above (Figs. 6a–c). However, models without an SWS during ENSO events exhibit two notable differences compared to observations or models with an SWS: 1) larger rainfall in the ITCZ than in the SPCZ and 2) SST underlying the ITCZ appear much warmer. Both changes are highlighted by looking at the differences between the models with and without the SWS (Fig. 6d). Precipitation differences of up to 4 mm day$^{-1}$ are found, whereby the models with the SWS are wetter in the western equatorial Pacific and drier in the northwestern Pacific. The rate of precipitation in these regions is significantly related to the magnitude of the SWS during all event types. Furthermore, the models with the SWS have cooler SST (up to 1.2°C) underlying the ITCZ than those without, and they also have a less pronounced cold tongue bias in the central Pacific. It has
been suggested that weaker gradients of SST facilitate a shift in convection zones (Cai et al. 2014). Thus, we expect the meridional gradient of SST between the equator and north off-equator regions, which is weaker in models without an SWS, to favor the shift in convection zone from SPCZ to ITCZ in these models. This is supported by calculating the coefficient of determination between the meridional gradient of SST and the magnitude of the modeled SWS, as we find a statistically significant relationship in all event types (Table 1). Another feature revealed by Fig. 6d is that models without an SWS tend to also exhibit weaker North Pacific trade winds owing to weaker zonal SST gradient.

c. Possible drivers of the SWS—Evidence from a multilinear regression

The results presented in sections 4a and 4b above suggest that the model’s mean climate and its representation of ENSO both impact the magnitude of the modeled SWS. To quantify the dependency of the SWS on these variables described above (Table 1), we conduct multiple-linear regressions (Wilks 2006) between the SWS, defined in section 3a, and a set of metrics each related to the possible driving mechanisms of the SWS, as listed in Table 1. As with the linear regressions presented in Table 1, each model’s ENSO event composite mean is computed, then the relationship (regression) between the indices is computed across the ensemble of models. We emphasize that the purpose of this analysis is not to generate a set of SWS predictors. Rather, the intent is to gain insight into the SWS dynamics, by analyzing its possible link to mean state metrics and their ENSO-related values, along with the horizontal resolution in the atmospheric model.

Given the large number of possible combinations of explanatory variables listed in Table 1, only those regressors with the highest $R$ squared values are taken into account. These include the three climatological values in DJF and the three anomalous variables, each of which we consider to be physically linked with the SWS. For each type of event, there are four multiple-regression models, shown in Table 2, which consist of (i) the six variables mentioned above, (ii) the three climatological values, (iii) the three anomalous values, and (iv) the meridional gradient of DJF climatological SST and rainfall anomaly in the northwestern Pacific, which have the highest correlation in the single linear regression (Table 1). The highest (significant) squared multiple correlations are up to 0.36, 0.60, and 0.51 for strong El Niño, moderate El Niño, and La Niña, respectively.

Interestingly, the resulting correlation is not the sum of the individual correlations, which highlights that each of these variables is not linearly independent. For instance, the climatological meridional gradient of SST and the ENSO-related anomalous precipitation in the northwest equatorial Pacific are linearly related ($R$ squared = 0.39, 0.46, and 0.46 for strong El Niño, moderate El Niño, and La Niña, respectively). As the latter variable is also related to the Philippine anticyclone development (i.e., how well the SWS is simulated; Fig. 3), the meridional gradient of SST in each model is expected to be a potentially important driver for both precipitation in the northwest equatorial Pacific and the SWS. It is also interesting to note that a large portion of the multilinear regression ($R$ squared) can be recovered when simply considering the climatological gradients of SST, precipitation, and wind stress and that this combined effect is not dissimilar to that which can be achieved with the meridional gradient of climatological SST alone. Again, we highlight the potential
importance of the meridional gradient of climatological SST as a driver of the SWS. Further experimentation, however, is needed to better understand the dynamics behind this link. We note that the coefficients of these two explanatory variables are statistically significant in most of our regression models. In addition to these two variables, including the rest of the regressors leads to an increase in the explained variance of the SWS for La Niña (from 39% to 51%), whereas no large contribution is found for strong El Niño (from 36% to 39%) and moderate El Niño (from 57% to 60%). We also notice that, given a variable, most (with the exception being SST anomalies) correlation coefficients are larger for moderate than for strong El Niño events (Table 1), which is consistent with the atmospheric nonlinear interaction between ENSO and the Pacific warm pool annual cycle (C-mode).

We emphasize that correlation, of course, does not necessarily imply causality. The association between the SWS and the anomalous variables described above may simply indicate symptomatic changes; however, we believe that this is unlikely to be the case for the climatological variables.

5. Seasonal synchronization and SWS

A well-known characteristic of ENSO events is their tendency to peak at the end of the calendar year, and as outlined in section 1, previous studies have proposed that the SWS plays a significant role in El Niño phase locking and therefore in the seasonal modulation of air–sea coupling strength. To further verify this hypothesis, we now examine the connection between ENSO seasonal synchronization and the SWS in the CMIP5 coupled models.

Figure 7 shows the composite Niño-3.4 region (defined in section 2c) SST anomaly evolution during a 13-month period (6 months before and 6 months after the peak) for the ensemble mean of CMIP5 models with SWS (CMIP5 with SWS) and without SWS (CMIP5 without SWS) versus observations for comparison. The maximum amplitude in CMIP5 with SWS (2.2°C) is roughly the same as the observed (2.1°C) and larger than that seen in CMIP5 without SWS (1.8°C). A t test is conducted to assess the statistical significance (at the 95% level) of the differences in the modeled composites, and statistically significant differences are denoted by the gray shaded area in Fig. 7. It is found that for strong El Niño events, the CMIP5 with- SWS and CMIP5 without SWS are significantly different during the development and mature phase. It is clear that the SST anomalies of the CMIP5-with-SWS models decay at a much faster rate than the CMIP5-without-SWS ensemble. To quantify the strength of this decay, we calculate the average of the monthly difference in the Niño-3.4 index between the peak of the event and 6 months after. The resulting average SST anomaly decay is $-0.34^\circ C \text{ month}^{-1}$ in CMIP5 with SWS, which is much stronger than the $-0.23^\circ C \text{ month}^{-1}$ seen in CMIP5 without SWS. It is interesting to note, however, that both values are lower than average SST anomalies decay observed during strong El Niño events ($-0.45^\circ C \text{ month}^{-1}$).

For moderate El Niño events, in contrast, no statistically significant difference is seen between the two modeled composite means throughout the whole period analyzed (Fig. 7b). The maximum values between CMIP5 with SWS and CMIP5 without SWS are approximately the same ($\sim 1^\circ C$), which is somewhat expected given these events must fall within the range of 0.5° and 1.5°C, and their decaying rates ($\sim 0.12^\circ$ and $-0.10^\circ C \text{ month}^{-1}$, respectively) are also highly similar. As is the case for strong events, the decaying rate for moderate El Niño is underestimated compared with observations ($\sim 0.19^\circ C \text{ month}^{-1}$).

In contrast to moderate El Niño events, there is a statistically significant difference between the two composite means during the mature phase for La Niña events (Fig. 7c). In particular, the peak magnitude is higher ($\sim 1.2^\circ C$) in CMIP5 with SWS compared to CMIP5 without SWS ($\sim 0.8^\circ C$), and the peak in the latter set is much less pronounced. Additionally, the decay of SST anomalies following the event peak is larger in CMIP5 with SWS (0.13°C month$^{-1}$) compared to CMIP5 without SWS (0.08°C month$^{-1}$), with both values again lower than observed (0.14°C month$^{-1}$).

We note that, given a certain magnitude of an ENSO event, its decaying rate is larger in CMIP5 with SWS than that in CMIP5 without SWS. Thus, the fact that the decay of SST anomalies following the event peak is lower in CMIP5 without SWS is owing to not only the lower magnitude of the events but also the lack of the SWS.

To further elucidate this feature of ENSO phase locking in relation to the SWS, Fig. 8 shows the percentage of ENSO events peaking in each calendar month for models with and without SWS compared to observations. The four observed extreme El Niño (1888/89, 1902/03, 1982/83, and 1997/98) all reached their maximum amplitude in NDJ (Fig. 8a). In comparison, in CMIP5 with SWS, 60% of strong El Niño events peak during NDJ, consistent with observations, whereas only 28% strong El Niño events peak in NDJ in CMIP5 without SWS. In addition, a relatively large proportion ($\sim 38\%$) of the modeled strong El Niño events peak erroneously during April–June in CMIP5 without SWS. The number of strong events erroneously peaking during April–June is only 6% in models with an SWS. Such a clear difference between the CMIP5 with SWS
and CMIP5 without SWS is not seen for moderate El Niño events, as ~30% of event peaks occur during October–December (OND) regardless of whether models accurately produce the SWS (Fig. 8b). In the observations, 60% of moderate El Niño events peak during OND, while 76% of La Niña events peak during NDJ. Some CMIP5-with-SWS and CMIP5-without-SWS differences are found, with 41% and 23% of La Niña events, respectively, peaking in NDJ (Fig. 8c).

Finally, following Bellenger et al. (2014), where they pointed out a large spread in CMIP5 ensemble ENSO variability, we now explore whether this behavior is partially due to how well models can reproduce the SWS. Figure 9 displays the standard deviation of the normalized Niño-3 index (i.e., SST anomalies averaged over 5°S–5°N, 150°–0°W) for each calendar month in the observations and models, where the models are split into those with and without a realistic SWS for the three event types and the CMIP5 multimodel ensemble mean. The seasonal cycle in the observations shows a clear maximum of SST anomaly during November–January and a minimum during March–April. Although the CMIP5-with-SWS ensemble exhibits a large spread and a smaller range, there is a tendency for a boreal winter maximum, as observed, and a minimum around April–June, which lags that observed by one month. These two limit values occur during the opposite seasons in CMIP5-without-SWS ensemble, which is consistent
with the tendency for some ENSO events to peak in the wrong time of the calendar year in those models, as described above. The multimodel ensemble mean is in close agreement with the CMIP5 with SWS (Fig. 9). However, its spread is larger than CMIP5 with SWS around April–June and August–December, coinciding with the maximum and minimum peaks in CMIP5 without SWS, respectively.

Thus, in summary, ENSO phase locking and its termination rates appear much more realistic in models with an SWS than models without an SWS for strong El Niño and La Niña events, especially for El Niño. However, as noted in the abstract, the models do underestimate the seasonal phase-locking tendency of ENSO events, and this is only partially improved by focusing on the CMIP5 models that accurately reproduce the SWS. As to whether the improvements in SWS representation in the CMIP5 models with SWS is due to the more realistic synchronization of ENSO events, we revert to past literature that shows that SWS can be generated for arbitrary frequencies of ENSO anomalies (Spencer 2004; Stuecker et al. 2015). Further to this, the study of Abellán and McGregor (2016) suggests that the SWS plays a crucial role in the synchronization of ENSO events to the seasonal cycle.

### a. WWV changes

It has been previously shown that variability in WWV, and hence heat content, in the tropical Pacific is related to the dynamics of the ENSO cycle (Wyrtki 1985; Cane...
water builds up in the equatorial Pacific prior to El Niño, and the recharge/discharge oscillator (RDO) theory proposes that warm water is discharged during El Niño as a consequence of equatorward transport of warm water. Then, the equatorial region is discharged of heat during El Niño, which ultimately sets up conditions favorable for the termination of the event. The fact that the SWS enhances the pre-event peak WWV recharge and the postevent peak WWV discharge effectively links the WWV with the seasonal cycle and provides a mechanism for the seasonal synchronization of the events.

Thus, in order to understand why the CMIP5 models are underestimating this phase locking, in spite of realistically producing the SWS we focus on the WWV changes driven by the SWS. Changes in WWV are generated by transports that converge/diverge in the equatorial region and defined here as transport differences at 5°S \((V_{5S})\) and 5°N \((V_{5N})\), \((V_{5S} - V_{5N})\), which represents the convergent meridional transport. Now, rather than calculating total transports in each model, which would make it difficult to distinguish the role of the SWS, we seek to identify the transports and WWV changes related to the wind stress changes that occur during the SWS. First, the wind stress changes that occur during the SWS are identified as the average wind stresses during the FMA season minus the ASO average wind stresses (as shown in Fig. 3). As McGregor et al. (2014) demonstrated that the WWV changes generated by the SWS are largely forced by surface Ekman transport changes, here we simply calculate the SWS induced changes in WWV from the meridional Ekman transport of the SWS (Fig. 3). It is worthwhile to note that the SWS-induced WWV changes represent approximately 25%–30% of the estimated total WWV changes in the CMIP5 models (estimated using NDJ Sverdrup transport during event years; not shown). Thus the CMIP5 model results are consistent with the modeled results of McGregor et al. (2014, their Fig. 7), which suggested that the SWS should play a prominent role in the termination of modeled ENSO events. We note that using Sverdrup transports to estimate WWV changes may overestimate the magnitude of the changes as the interior transports are often partially compensated by transports at the Pacific Ocean western boundary. We then seek to identify the relationship between these SWS-induced WWV changes during ASO prior to the peak of the ENSO event and their relationship with the magnitude of the events, as well as SWS-induced WWV changes during FMA after the event peak and their relationship with the decay of SST anomalies (event termination).

Figure 10 highlights a statistically significant linear relationship between the SWS-induced WWV changes during ASO preceding the event peak and the magnitude of the ENSO event peak (SST anomalies during DJF) \((Figs. 10a–c)\). This relationship is consistent with the RDO theory \((Meinen and McPhaden 2000)\), which links the two metrics; however, the recharging due to the SWS is distinct from that explicitly covered by the RDO theory. It is also revealed that models with weak SWS (light green dots) tend to exhibit weak changes in WWV, although the relationship between the SWS and changes in WWV is significant only for La Niña \((r = 0.43; \text{not shown})\). However, those models with strong SWS (dark green dots) do not necessarily show strong changes in WWV. This is not unexpected, as it is the magnitude and zonal extent of the wind changes that drives an oceanic response, not only the latitude of the maximum.

To understand how the SWS changes in WWV after the event peak (FMA during the decaying year) impact the SST anomalies decay of each event type, Fig. 10 also displays the FMA WWV changes plotted against the post-ENSO-event peak SST anomaly decay. It is noteworthy that again a statistically significant relationship is found for ENSO events \((Figs. 10d–f)\), reaching the maximum correlation for strong El Niño \((r = 0.60)\). Thus, if the SWS-induced discharge (recharge) of heat content for El Niño (La Niña) is large, the termination of the event tends to be more rapid than that with small WWV changes. It is interesting to note that multimodel mean WWV change for moderate El Niño is much lower than that observed, which may help to explain why these events are not as phase locked as the observations \((Fig. 8b)\). Also illustrated here are the symmetries between La Niña and moderate El Niño events for values of the Niño-3.4 index, SST anomaly decay, and WWV changes. Hence, this analysis highlights how the SWS modulates the evolution of the WWV changes in the equatorial Pacific Ocean and effectively links these changes with the seasonal cycle; the recharge of the WWV occurs prior to the El Niño event (represented here in ASO season), whereas the discharged state is obtained after the peak (represented here in FMA season).

6. Summary and conclusions

The goal of our study was to address the following questions: 1) Do the CMIP5 models reproduce a realistic southward wind shift (SWS)? 2) What variables are related to the SWS in CMIP5 models? 3) What is the role of the SWS in the seasonal synchronization of modeled ENSO events? First, however, we define three ENSO event types: El Niño events are separated into strong and moderate categories while La Niña events have only the one category (see section 2c).
It was demonstrated that the magnitude of zonal wind stress anomaly during ENSO events is clearly underestimated and its spatial pattern extends too far into the western Pacific, although the latter has been incrementally improved in CMIP5 with respect to CMIP3 (Capotondi et al. 2006; Lee et al. 2013). In terms of capturing the SWS, it is encouraging that the vast majority (81%–86%) of CMIP5 models successfully captures the observed SWS.

**Fig. 10.** Scatterplots showing the modeled relationship (a)–(c) between the magnitude of ENSO events in DJF and WWV changes in August–October and (d)–(f) between the termination rate (defined in section 5) and WWV changes in February–April. Note that the colors of the dots indicate the intensity (in °latitude) of the SWS and the slopes of the regression lines are multiplied by $10^{14}$. The squares, with a red outline, represent the observed values, whereas the big circles indicate the multimodel ensemble means. The average value in ASO and FMA [i.e., (ASO + FMA)/2] is subtracted for changes of WWV in both ASO and FMA in order to emphasize the role of the SWS in WWV changes. The spatial patterns of zonal wind stresses anomalies used to compute WWV changes are shown in Fig. 3.
during some of the three types of ENSO events (strong El Niño, moderate El Niño, and La Niña), with mean latitude biases of $-1.4^\circ$, $0.3^\circ$, and $-0.8^\circ$, respectively (see section 3a for SWS definition). We found in addition that 65% of models reproduce an SWS for all types of ENSO events, whereas only 2 out of 34 models (IPSL-CM5A-LR and IPSL-CM5A-MR) fail to simulate the SWS for all three event types.

In examining the factors that are related to the performance of CMIP5 models in simulating the SWS, we first classify the models according to their ability to represent the SWS during ENSO events and then make model ensembles with and without the SWS. We then composite means of SLP, precipitation, and SST anomaly patterns. Our results indicate that most models have a problem reproducing the zonal location of the anomalies in zonal wind stress, precipitation, and SST, as documented in past studies (e.g., Kug et al. 2012; Capotondi and Wittenberg 2013; Zhang and Sun 2014; Ham and Kug 2014; Taschetto et al. 2014). However, here we have demonstrated that these biases in models without an SWS are much larger than those in models with an SWS. Furthermore, the seasonal differences of zonal wind stress and SLP anomalies prior to the peak of the events (August–October) and after the mature phase (February–April) are underestimated in all of the CMIP5 models; however, this is most pronounced in CMIP5 models that do not accurately produce an SWS. It is also clear from our analyses that the anomalous values of SST and rainfall during the mature phase (DJF) of La Niña and strong El Niño are weaker in models having a poor simulation of the SWS compared to models with an SWS, whereas no striking difference is seen for moderate El Niño. To further explore differences between models with and without an SWS, we analyzed the climatological SST, precipitation, and zonal wind during DJF over the tropical Pacific. It was shown that models without an SWS exhibit stronger ITCZ, warmer underlying SST, and weaker trade winds over the north tropical Pacific compared to models with an SWS, in addition to westward extension of the cold tongue.

To provide a more quantitative idea as to the relationship between the composite difference and the SWS, we measured the magnitudes of modeled SST anomalies in the year of ENSO (a proxy for the phase locking of events) in the models without an SWS shows maximum and minimum anomalies during the opposite season compared to models with an SWS and observations (i.e., minimum in April–June and maximum in November–January). While those models with the SWS are much more accurate in the representation of the seasonal synchronization, they underestimate their magnitude.

To gain insight into this, SWS-driven WWV changes were calculated during the lead-up to ENSO peaks and after the event peaks. It was shown that statistically significant linear correlations exist between the SWS-induced WWV changes in August–October and the magnitude of the event in DJF and between the SWS-induced WWV changes in February–April and the decay-of-event SST anomalies. We also find that the models dramatically underestimate the magnitude of SWS-induced WWV changes during moderate El Niño events, which may explain why the SWS does not appear to impact the evolution of events.

Thus, these results emphasize the importance of simulating the SWS for two overarching reasons: 1) this is associated with a decrease in some well-known biases in both mean state and ENSO-driven anomalous values, and 2) this yields a better performance in the
synchronization to the seasonal cycle of ENSO events, particularly important for ENSO teleconnections (e.g., Webster et al. 1998). It is interesting to note that although the majority of models can produce an SWS, they largely underestimate the seasonal phase locking of ENSO. Thus, we highlight that while the SWS is an interesting metric to examine, it is also the magnitude and zonal extent of the wind changes that accompany this SWS that drives the changes in WWV. Further to this, there are likely more processes involved in the spring termination of ENSO events than considered here, such as the seasonally changing cloud feedbacks (Dommengen and Yu 2016; Rashid and Hirst 2015).

Acknowledgments. This study was supported by the Australian Research Council (ARC) through Grant DE130100663, with additional support coming via the ARC Centre of Excellence for Climate System Science. We also acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, for producing and making available their model output. This work was undertaken with the assistance of resources from the National Computational Infrastructure (NCI), which is supported by the Australian Government. CMAP Precipitation and ERA-Interim data by ECMWF. The authors would also like to thank three ERSST data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, and ERA-Interim data by the Australian Government. CMAP Precipitation and ERA-Interim data by ECMWF. The authors would also like to thank threeanonymous reviewers for their comments and suggestions, which helped substantially improve the paper.

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