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Key Points:

- Variations in the Southern Hemisphere semiannual oscillation can affect El Niño development
- A large-amplitude semiannual oscillation can contribute to the development of a strong eastern Pacific El Niño event
- A small-amplitude semiannual oscillation can contribute to the development of a relatively weak central Pacific El Niño event

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The role of the Southern Hemisphere semiannual oscillation in the development of a precursor to central and eastern Pacific Southern Oscillation warm events

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Abstract The semiannual oscillation (SAO) is a twice-yearly northward movement (in May-June-July (MJJ) and November-December-January (NDJ)) of the circumpolar trough of sea level pressure (SLP) in the Southern Hemisphere with effects throughout the troposphere. During MJJ the second harmonic of SLP, describing the SAO, has low values of SLP north of 50°S in the subtropical South Pacific, while the first harmonic, which is dominant over the Australian sector, increases to its peak. This once-a-year peak in negative SLP gradients (decreasing to the east) between Australia and the ocean to its east extends to the equatorial Pacific. Southern Oscillation warm events since 1950, with an intensification of this seasonal cycle, have larger-amplitude SST anomalies in the eastern equatorial Pacific in MJJ and during the following mature phase in NDJ. Weak amplification of the seasonal cycle in MJJ tends to be followed by larger-amplitude SST anomalies in the central equatorial Pacific during NDJ.

Plain Language Summary Variations in the seasonal cycle in the Australian-Pacific region can affect where and how El Niño events develop.

1. Introduction

The sea level pressure (SLP) in high and lower latitudes of the Southern Hemisphere has long been known to be dominated by a second harmonic because the circumpolar trough moves meridionally twice a year in the three ocean basins [*van Loon*, 1967; *van Loon and Jenne*, 1972; *Raphael*, 2004; *Ackerley and Renwick*, 2010]. The SLP north of 50°S thus has lowest values in May-June-July (MJJ) and November-December-January (NDJ) when the trough of low pressure moves northward, while farther south around Antarctica the minima are in February-March-April (FMA) and August-September-October (ASO) when the trough contracts and intensifies [*van Loon*, 1967, 1972; *van Loon and Rogers*, 1984]. The mechanism for the SAO was determined to arise from the different heat balances at the surface. Those processes produce contrasting seasonal evolutions of surface temperatures over the circumpolar Southern Ocean and the Antarctic region such that the meridional temperature gradient, and thus baroclinicity, intensifies twice per year in FMA and ASO [*van Loon*, 1967]. This mechanism was subsequently confirmed with more recent data [*Meehl*, 1991; *Meehl et al.*, 1998]. There is a large and dominant first harmonic of SLP over the Australian sector with highest values in early southern winter peaking in June [*van Loon*, 1972]. Thus, once a year in MJJ, a strong negative SLP gradient in the southwest Pacific arises from the difference between the first harmonic of SLP over Australia and the second harmonic of SLP over the South Pacific.

Subsequent studies have confirmed that the SAO in the South Pacific, with an anomalous negative SLP gradient extending from the southwest Pacific to the equatorial Pacific, can provide a precursor to the development of Southern Oscillation warm events as a necessary condition (colloquially termed El Niño events and referred to here as "Southern Oscillation (SO) warm events") [*van Loon and Shea*, 1987; *van Loon et al.*, 2003; *Stephens et al.*, 2007; *Hong et al.*, 2014; *Hamlington et al.*, 2015]. In some years when the circumpolar trough in the South Pacific moves northward in the SAO in MJJ, the Pacific subtropical high at the same time weakens, the associated SLP gradient in the equatorial Pacific slackens and the trade winds weaken, equatorial upwelling weakens, and equatorial Pacific SSTs rise.

Certain SO warm events are stronger than others and have maximum warming occurring at different longitudes [*Capotondi et al.*, 2015]. There has been a growing recognition that events can be categorized as those with largest warming in either the central equatorial Pacific (CP) events or eastern equatorial Pacific (EP) events during their peak, typically in northern winter [e.g., *Trenberth and Stepaniak*, 2001; *Larkin and Harrison*, 2005; *Ashok et al*., 2007; *Kug et al*., 2009]. The development of EP and CP SO warm events has been shown to have different linkages to conditions in the northern [e.g., *Yu and Kim*, 2011] or southern [e.g., *Zhang et al*., 2014] Pacific. However, the nature of the origins of the precursor conditions has remained unclear, particularly with regards to which plays a more important role.

Here we note that previous studies cited above that show conditions in MJJ, as part of the seasonal cycle in the Australia-Pacific region of the Southern Hemisphere, are important for the development of an SO warm event. We show that the amplitude and phase of the seasonal cycle of the SAO over the Pacific and the first harmonic over Australia can produce conditions in MJJ in the subtropics and midlatitudes of the Australia-Pacific sector that can then be necessary, but not always sufficient, for the development of a SO warm event that peaks in NDJ. We also will examine conditions during MJJ associated with the SAO to determine if there is a connection to the subsequent amplitude or location of greatest warming (either CP or EP) in the subsequent peak season of NDJ.

2. Data and Methods

We use sea level pressure data from Hadley SLP and surface winds from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalyses, and these are available and documented at https://www.esrl.noaa.gov/psd/cgi-bin/data/getpage.pl. Sea surface temperature data are from *Hurrell et al.* [2008] available from ftp://ftp.cgd.ucar.edu/archive/SSTICE. Upper ocean temperature data are from the SODA2.2.4 forced by 20Crv2 from 1871 to 2010 (http://www.atmos.umd.edu/~lchen/SODA2.2.4_Description.html). We refer to a compilation of SO warm events since 1950 from http://ggweather.com/enso/oni.htm using the Oceanic Niño Index (ONI) defined as the running 3 month mean SST anomaly for the Niño 3.4 region (5°N–5°S, 120°W–170°W). SO warm events in that compilation are categorized as weak (with a 0.5°C to 0.9°C SST anomaly), moderate (1.0°C to 1.4°C), strong (1.5°C to 1.9°C), or very strong (≥2.0°C) and must have equaled or exceeded the threshold for at least three consecutive overlapping 3 month periods. Following previous studies regarding precursor conditions involving the SAO [e.g., *van Loon and Shea*, 1987], we examine conditions during the year of onset of an SO warm event (“year 0”) and do not consider the second year of two consecutive events.

We focus on conditions in the MJJ season of year 0 for the SO warm events defined using the ONI index above, and then relate MJJ conditions to subsequent SO warm event development during the peak phase in NDJ. MJJ conditions fall into two categories, one with greater warming in the eastern equatorial Pacific (termed “MJJ-EP”) and the other with almost no warming there but somewhat greater warming in the central equatorial Pacific (termed “MJJ-CP”). Starting with the compilation of SO warm events based on ONI described above, MJJ-EP years are defined based on standardized June–July season-averaged Niño1 + 2 (80–90°W, 0–10°S) SST anomalies for those SO warm event years that have greater than 0.6 standard deviations, and MJJ-CP years less than 0.6 standard deviations. This produces MJJ-EP SO warm event years 0 of 1951, 1957, 1965, 1972, 1976, 1982, 1997, and 2015 and MJJ-CP years 0 of 1963, 1968, 1979, 1986, 1991, 1994, 2002, 2004, 2006, and 2009. Using the strength scale from the published compilation above, all of the MJJ-EP years defined in this way evolve into either strong or very strong SO warm events (except for 1951 and 1976), while all the MJJ-CP years are either moderate or weak SO warm events. As we will show below, the MJJ-EP years end up producing a preponderance of what is more typically termed “EP” warm events in the literature, as defined for the northern winter peak phase as discussed earlier, and MJJ-CP years are often characterized by “CP” warm events during the northern winter peak phase. Therefore, we use SST anomalies in MJJ associated with the SAO as a starting point to study the nature of the evolution of SO warm events leading to the peak phase in NDJ in terms of the longitudes of where highest-amplitude positive SST anomalies occur.

Comparison of the MJJ-CP years and MJJ-EP years above shows that many end up with consensus definitions of CP and EP events for the subsequent peak of the SO warm event in NDJ. For example, *Yu et al.* [2012] chose CP and EP events using three different definitions. The consensus of the three definitions shows that all but two (1957, 1965) of the MJJ-EP years end up being consensus EP events during northern winter, and all but two of the MJJ-CP years (1986 and 2006) end up being consensus CP events. Thus, there is considerable

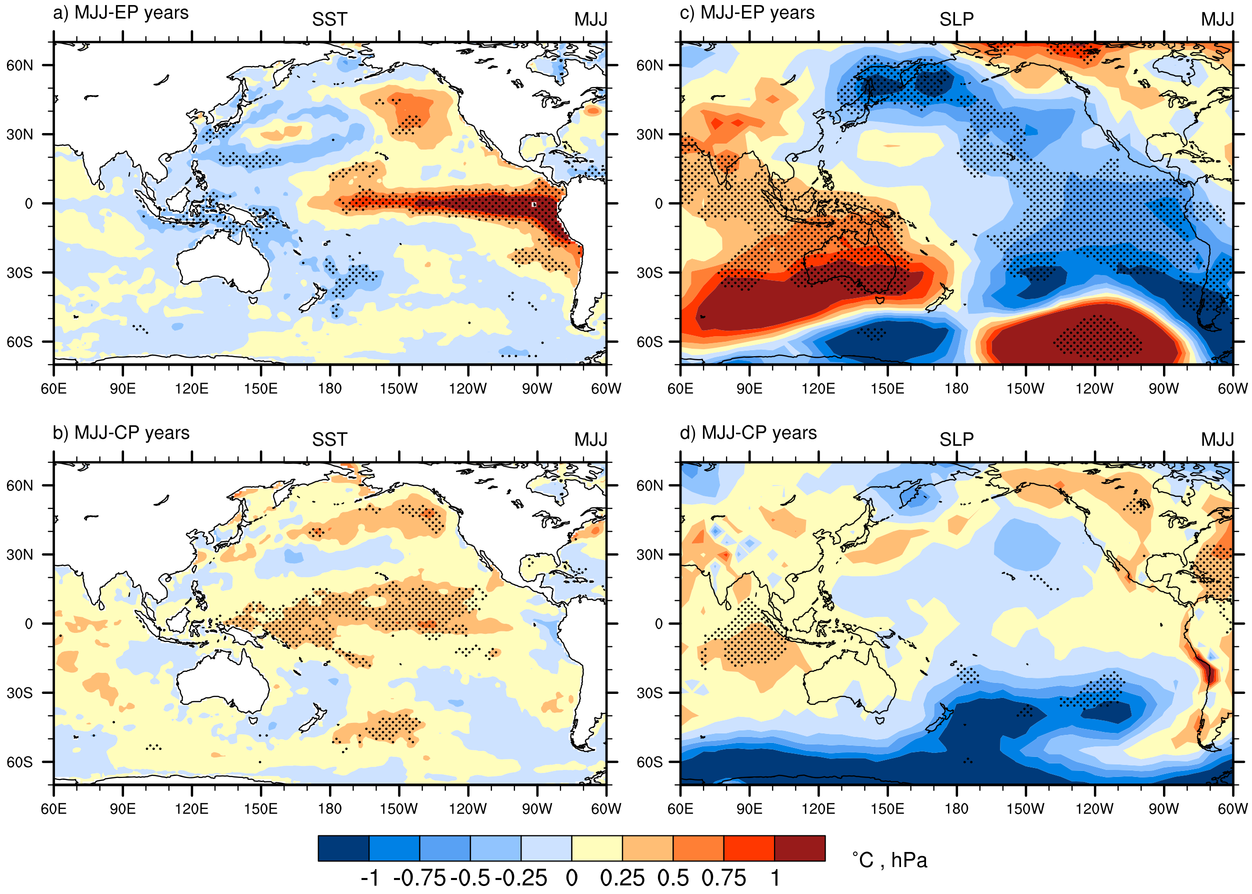

Figure 1. (a) Composite MJJ SST anomalies from *Hurrell et al.* [2008], year 0, MJJ-EP years minus climo (1951–2010); stippling indicates significance at the 95% level with a two-sided *t* test and an equivalent sample size test which takes into account the correlation of the samples. (b) Same as in Figure 1a except for MJJ-CP years. (c) Same as in Figure 1a except for MJJ-EP SLP anomalies from Hadley SLP. (d) Same as in Figure 1c except for MJJ-CP years.

overlap in the MJJ and peak phase definitions. Using the *Yu et al.* [2012] definitions to form MJJ composites for consensus EP and CP events, there are similar results in MJJ to the composites formed by defining contemporaneous MJJ SST anomalies (not shown). Additionally, if the Niño1 + 2 definition for obtaining MJJ-EP and MJJ-CP years above is applied to peak phase conditions (e.g., in the following NDJ), all the MJJ seasons are the same as listed above except for 1951 and 1976, with comparable anomaly patterns. This should not be surprising given the large and consistent SST signals for the relatively large number and types of events such that a year or two more or less in the composite reassuringly does not substantially change the composite anomaly pattern. For our purposes, we will start with the MJJ-EP and MJJ-CP years defined above, and contrast the SAO signatures of SLP, SST, and surface wind in the two sets of years to elucidate SAO contributions to the evolution of different types of SO warm events. Significance testing of the anomalies is performed with a two-sided *t* test and an equivalent sample size test which takes into account the correlation of the samples.

3. Results

Composite SST anomalies for the MJJ season are shown for MJJ-EP years (Figure 1a) and MJJ-CP years (Figure 1b). There is a clear difference in patterns, with the mean MJJ-EP years having positive SST anomalies greater than +1.5°C concentrated in the eastern equatorial Pacific, while the mean MJJ-CP years have small-amplitude SST anomalies of considerably less than +0.5°C spread from about 100°W westward across the tropical Pacific. There are even small-amplitude negative SST anomalies in the far eastern equatorial Pacific for the mean MJJ-CP years in the location where positive SST anomalies are approaching their largest values for MJJ-EP years.

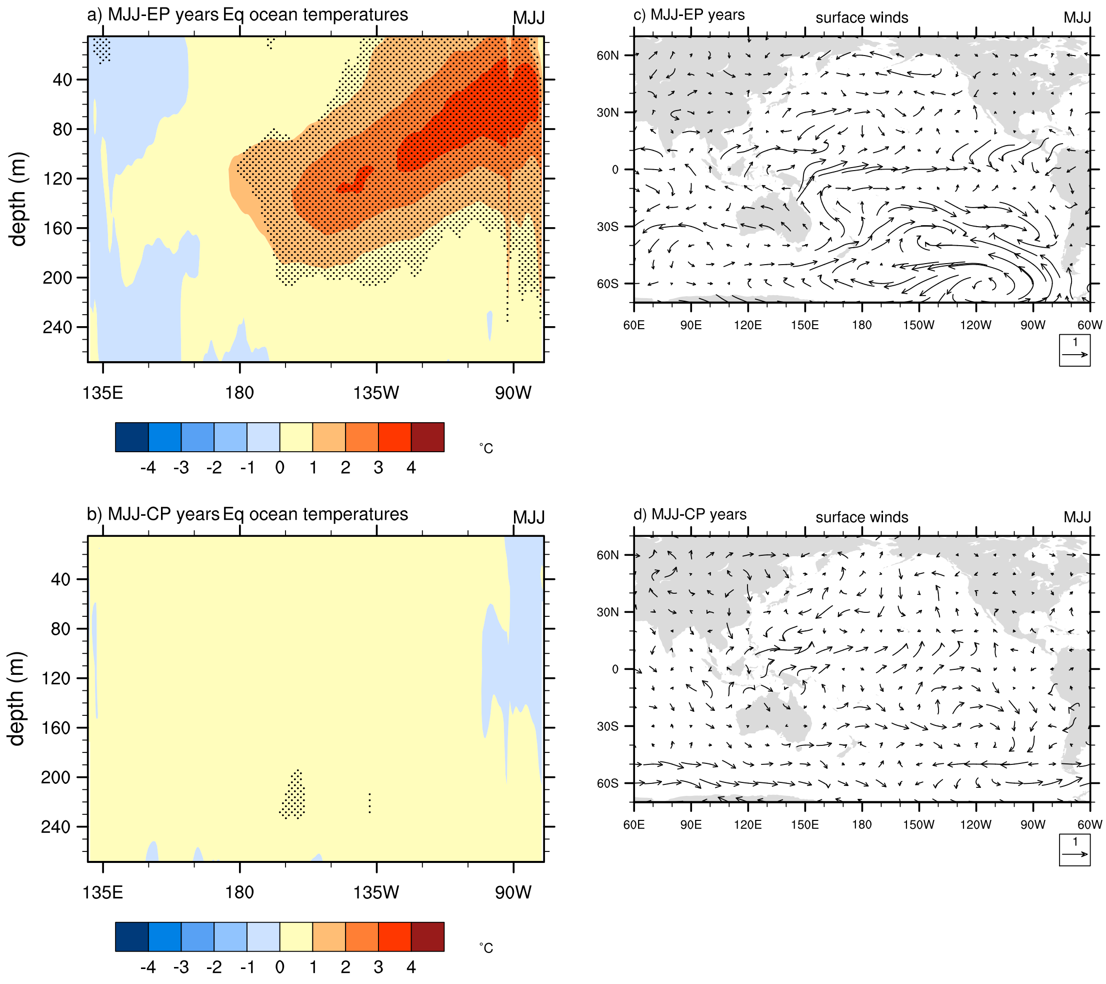

Figure 2. (a) Equatorial Pacific vertical section of upper ocean temperature anomalies, SODA2.2.4 forced by 20Crv2 from 1871 to 2010, MJJ-EP years minus climo; stippling indicates anomalies significant at the 95% level from a Student's *t* test. (b) Same as in Figure 2a except for MJJ-CP years minus climo. (c) Surface vector wind anomalies, MJJ-EP years minus 1951–2010 climo, m s^{-1}, from NCEP/NCAR reanalysis, direction designated by arrows, scaling vector at lower right of 1 m s^{-1}. (d) Same as in Figure 2c except MJJ-CP vector wind differences.

The MJJ SLP anomalies associated with those SST anomalies are shown for the MJJ-EP years (Figure 1c) and MJJ-CP years (Figure 1d). As with the SST anomalies, there are marked differences in these two patterns. For the MJJ-EP years in Figure 1c, the seasonal northward expansion of the circumpolar trough in the Southern Hemisphere in this season is amplified, with significant negative SLP anomalies near 30°S between about 160°W and 90°W of roughly −1 hPa and significant positive anomalies greater than +2.5 hPa near 50°S between about 160°W and 90°W, indicating that the MJJ decrease of SLP north of 50°S in the SAO seasonal cycle [*van Loon*, 1972; *van Loon and Rogers*, 1984] is occurring farther equatorward. Associated negative SLP anomalies extend to the equator in the Pacific east of the dateline. In the Australian sector, there is a simultaneous enhancement of the seasonal cycle with rises of SLP, producing positive SLP anomalies of over 1 hPa over Australia, with positive anomalies extending across the equator in the western Pacific. This is a consequence of the enhancement of the seasonal cycle, with the seasonal positive SLP anomalies over Australia having even larger positive values, and the seasonal northward expansion of the trough and pressure falls in the eastern Pacific occurring even farther north to produce more negative statistically significant SLP anomalies in the subtropical South Pacific. The resulting anomalous west-east SLP gradient in the western Pacific produces consistent anomalous southerlies in the southwestern Pacific and anomalous westerly surface winds in the equatorial western Pacific for MJJ-EP years on the order of 2 m s^{-1} (Figure 2c; typical interannual standard deviations are between 1 and 1.25 m s^{-1} (not shown)).

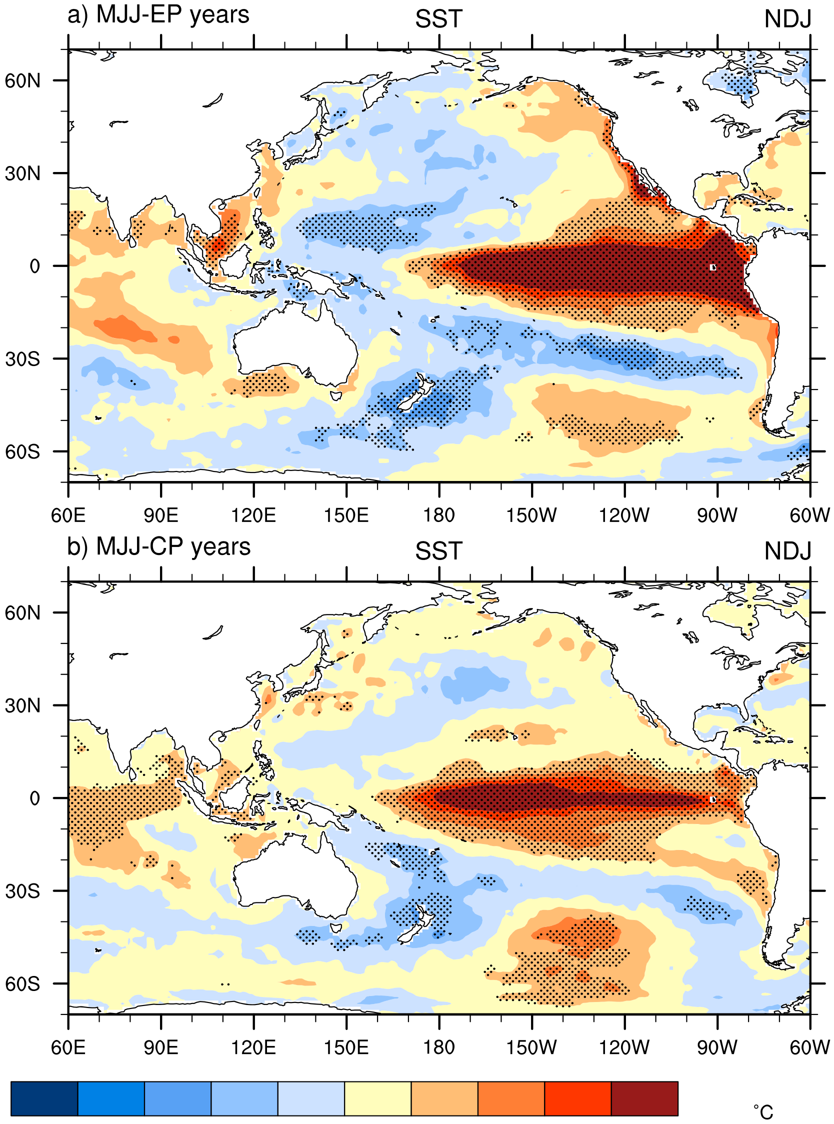

Figure 3. (a) Same as in Figure 1a except for year 0 MJJ-EP SST anomalies for the NDJ season. (b) Same as in Figure 3a except for MJJ-CP NDJ SST anomalies.

For the MJJ-CP years, the pressure falls in the Pacific are stronger farther south as evidenced by negative SLP anomalies near 40°S of about 1 hPa (Figure 1d), whereas seasonal pressure rises over Australia are near normal (i.e., very small SLP anomalies there in Figure 1d). The result is virtually no anomalous SLP gradient in the southwest Pacific and eastern equatorial Pacific such that the corresponding surface wind anomalies in the MJJ-CP years in those regions (Figure 2d) are mostly less than 1 m s^{-1}.

The anomalous SLP gradients noted above in the western Pacific that produce the westerly wind anomalies in the equatorial western Pacific could be expected to produce equatorial Kelvin waves that would act to deepen the thermocline and raise SSTs in the eastern equatorial Pacific in MJJ. Westerly wind-forced intraseasonal Kelvin waves and their effects on the thermocline and SST are regularly observed in the equatorial Pacific [e.g., *McPhaden*, 1999; *Roundy and Kiladis*, 2006; *McPhaden et al.*, 2015]. This is shown in Figure 2 where there are positive temperature anomalies in the subsurface eastern equatorial Pacific in the MJJ-EP years (Figure 2a) with anomalies over +3°C near 80 m depth, while the subsurface temperature anomalies in Figure 2b for MJJ-CP years are mostly less than +1°C with small negative anomalies in the far eastern equatorial Pacific.

Given this marked contrast between MJJ-EP and MJJ-CP years in MJJ of year 0 of the SO warm events, it could be expected that the outcomes during the peak of the events in northern winter/southern summer (mature phase) [*Rasmusson and Carpenter*, 1982] would be quite different as well. Indeed, Figure 3 shows November-December-January (NDJ; for the SAO-based season) positive SST anomalies greater than +1.5°C from 160°W to the coast of South America for MJJ-EP years, with maximum values of about +2.5°C near 100–120°W in the eastern equatorial Pacific. For MJJ-CP years in Figure 3b, the composite NDJ SST anomalies are smaller overall, with positive values of only roughly +0.5°C near the coast of South America, and maximum amplitude anomalies of about +1.5°C located farther west near 160°W.

Thus, we have shown that for the development of MJJ-EP SO warm events, there is an amplification of the seasonal cycle in the Australia-Pacific sector of the Southern Hemisphere, with larger-amplitude positive SLP anomalies in the first harmonic in MJJ over Australia, and a greater northward movement of the circumpolar trough in the SAO in MJJ with negative values near 30°S in the Pacific. This produces anomalous SLP gradients and surface wind anomalies that are conducive to weakening equatorial upwelling in the equatorial Pacific, and generating equatorial Kelvin waves that deepen the thermocline in the east. Both processes act to produce larger-amplitude SST anomalies farther east in MJJ-EP years compared to MJJ-CP years that do not have strong contributions from these anomalous processes. Therefore, the MJJ-CP years result in lower mean SST anomalies that set up farther west in the tropical central Pacific Ocean compared to the MJJ-EP years. This provides a connection between anomalies in the seasonal cycle in the Australia-Pacific region of the Southern Hemisphere, particularly the Southern Hemisphere semiannual oscillation in the subtropical and midlatitude Pacific, and interannual variability in the tropical Pacific.

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