The impact of global warming on sea surface temperature based El Niño–Southern Oscillation monitoring indices

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Sea surface temperature (SST) anomalies in the tropical Pacific are commonly used indicators for diagnosing the El Niño–Southern Oscillation (ENSO) state. Global warming has the potential to affect these indicators so that the indicators provide a less representative picture of El Niño/La Niña developments. The SST trend has not been uniform across the Tropics; hence, accounting for local trends may not account for widespread warming. A method is proposed to remove tropical SST trend from the Niño3.4 index, one of the most common indices for monitoring ENSO. The trend and climatology analysis periods are selected based on the Interdecadal Pacific Oscillation. The climatology period contains an equal number of years with positive and negative phases (1976–2014), while the trend is estimated over a longer period with no significant trend in the Interdecadal Pacific Oscillation (1962–2011). Furthermore, the trend is estimated using three SST datasets and sampling of the time period to account for uncertainty in measurements. Once the tropical trend is removed, new Niño3.4 values are calculated and a new ENSO classification proposed to re-classify ENSO events since 1976. The recent 3 years with the largest deviation due to global warming (2014–2016), once corrected contain the full ENSO cycle with neutral, strong El Niño, and La Niña years. These events based on the new classification align well with other ENSO predictors, such as outgoing longwave radiation and zonal wind at 850 hPa, particularly for marginal cases such as the 2016 La Niña event. These results have implications for how ENSO is monitored and predicted in relation to climate change.

KEYWORDS
climate change, ENSO, Interdecadal Pacific Oscillation, sea surface temperatures

1 | INTRODUCTION

Since the development of El Niño–Southern Oscillation (ENSO) monitoring tools in the late 1970s, sea surface temperature (SST) has been used as a key indicator for the current ENSO state. Particularly, central-eastern Pacific SSTs are thought to be one of the most sensitive single indicators for ENSO. At the same time, climate change has led to rising SSTs around the globe, although the warming is not uniform (Solomon and Newman, 2012; McGregor et al., 2014; Lim et al., 2016). The widespread tropical warming trend, if not accounted for, could partly offset cold events and overstate warm events in SST-based indices.

El Niño (La Niña) events are anomalous warm (cold) SSTs in the eastern equatorial Pacific along with changes in the atmospheric circulation patterns (Southern Oscillation). During La Niña events, the east–west cold–warm SST gradient is enhanced, which leads to increase in convection in the western Pacific and in the trade winds, which in turn leads to a strengthening of the SST gradient (termed the Bjerknes feedback; Collins et al., 2010). There are various
mechanisms that can promote or suppress La Niña or El Niño events (e.g., zonal wind bursts, Levine and McPhaden, 2017; and heat decrease in the western North Pacific Ocean, Guilyardi et al., 2003). The balance of these mechanisms and other feedbacks will lead to either the growth or decay of an event. While atmospheric-based indices (such as the Southern Oscillation Index [SOI]) are used in determining the ENSO state, many classifications have relied on SST-based indices (Horsfall, 2006).

There are a variety of SST indices to monitor ENSO. The first developed indices tended to use SSTs near the Peruvian coast (e.g., Quinn et al., 1978; Rasmusson and Wallace, 1983; SCOR, 1983). However, further investigation found that SSTs further to the west had higher predictability (Barnston and Ropelewski, 1991) and thought to be more strongly correlated to the ENSO phenomenon, particularly Niño3.4 (Barnston et al., 1997). The Niño3.4 index was adopted by the Climate Prediction Center, part of National Oceanic and Atmospheric Administration’s (NOAA) National Center for Environmental Prediction (NCEP), in 1996 (Trenberth, 1997) and has become one of the key indices for monitoring ENSO. To capture western Pacific SST variations, the Japan Meteorological Agency (JMA) often use the NiñoWest index, where negative values tend to occur during an El Niño (Kuriyama et al., 2012). In each of these cases, the SST-based indices cover a single box in the Pacific. Other indices that use multiple locations have been proposed, such as the Trans-Niño Index (Trenberth and Stepaniak, 2001), and those proposed by Ren and Jin (2011). However, as these indices have yet to gain widespread usage and may be less affected by the tropical warming trend, the focus here will be on the single box indices.

While it has been well established that SSTs around the world have warmed (Hartmann et al., 2013), the warming has not been uniform. There has been some evidence of a strengthening of the equatorial Pacific temperature gradient since 1900, particularly with regards to the warm pool in the western Pacific (Solomon and Newman, 2012). This difference between the east and west may be due to the initial response of ocean dynamical processes to surface warming (Luo et al., 2017). Strong warming in the Atlantic is also thought to have driven an intensification of the Walker circulation since the 1990s, thereby minimizing the warming in the eastern Pacific (McGregor et al., 2014). However, the warming pattern varies depending on time period considered, partly due inter-annual variability (Bordbar et al., 2017). Furthermore, the SST trend differs between datasets, even if the differences in the datasets’ mean climatology are small (Timbal and Hendon, 2011).

In the following sections we explore removing the background tropical warming trend from two SST-based ENSO indices on either side of the Pacific (Niño3.4 and Niño West), how such corrections impact the identification of past historical events, and implications for recent ENSO events.

2 | DATA AND METHODOLOGY

2.1 | Data

The various SST datasets exhibit differences in warming trends, therefore the amplitude of the trend is likely dependent on the data set. Here we use three SST datasets: Extended Reconstructed Sea Surface Temperature v5.0 (ERSST; Huang et al., 2017), Hadley Centre Global Sea Ice and Sea Surface Temperature v1.1 (HadISST; Rayner et al., 2003), and Centennial in situ Observation-Based Estimates (COBE; Ishii et al., 2005). The HadISST data set is primarily based on the Met Office Marine Data Bank, supplemented with International Comprehensive Ocean–Atmosphere Dataset (ICOADS), data from the Global Telecommunications System (GTS), and AVHRR SST (Rayner et al., 2003), at a resolution of 1 × 1° with monthly data available from 1870 to the near present. Similarly, COBE is based on the Kobe Collection, supplemented with ICOADS, buoys from Marine Environment Data Service of Canada, and GTS at a resolution of 1 × 1° and monthly data available from 1891 onwards (Ishii et al., 2005). The ERSST data set used primarily the ICOADS R3.0 data along with Argo float observations above 5 m (Huang et al., 2017), with any missing data replaced by interpolated data. The ERSST data set has the coarsest resolution of 2 × 2° available monthly from 1854 onwards. There are also differences in the bias adjustments and uncertainty estimates between the three datasets, although biases may still remain in the data (Kent et al., 2017).

2.2 | Study period

Data availability and natural variability on decadal timescales needs to be considered when determining the study period. It is well recognized that ENSO patterns display multi-decadal variability such as captured by the Interdecadal Pacific Oscillation (IPO; Power et al., 1999). Indeed, there have been two shifts noted in inter-annual variability in the tropical Pacific: the late 1970s (Wallace et al., 1998) and 1999–2000 (Hu et al., 2013; Wang and Ren, 2017). The latter phase was associated with a more La Niña like state, increase (decrease) in both the SSTs and precipitation anomalies in the western (eastern) Pacific (Hu et al., 2013).

To avoid incorporating natural variability when removing the global warming trend, the chosen period should encompass a period with no significant trend in the IPO. The Henley et al. (2015) tripole IPO index (TPI) is calculated using

$$TPI = R2 - \frac{R1 + R3}{2},$$

where the R values are the average SST for over the regions outlined in Figure 1 (R1: 25°–45°N, 140°E–145°W; R2: 10°S–10°N, 170°E–90°W; R3: 50°–15°S, 150°E–160°W).
A 13-year Chebyshev low-pass filter is then applied (Henley et al., 2015). The Mann–Kendall test calculated for 1962–2011 and each month independently found no significant trend (5% significance level). Therefore, the period over which the trend was calculated covers 1962–2011 where there was no significant trend in the IPO (Figure 2).

The climatology covers 1976–2014, with an estimated equal number of positive and negative IPO months to reduce the probability of the climatology being weighted towards either El Niño or La Niña events (grey box in Figure 2). The most recent years are estimated due to the application of a 13-year low-pass filter; however, there is at least an 80% probability that the values remain negative until 2014–2015 (Henley, 2017). The climatology period covers similar phases of the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), with the recent negative phase of the PDO lasting until 2014 (Screen and Francis, 2016; Zhang et al., 2018). The 1976–2014 period is also convenient in terms of data availability, quality, and coverage and compares well with the continued global warming since the mid-1970s (Meehl et al., 2009; Hartmann et al., 2013).

2.3 | Tropical SST trend

The SST trend varies across the Tropics and the entire globe (Figure 1). By averaging the SST trend over 30°S–30°N, spatial variations in tropical warming due to naturally occurring modes of variability are removed. A linear trend is calculated using ordinary least squares for each month independently, due to potential seasonal variations in the trend and therefore to reduce autocorrelation. The trend is assessed using the Spearman’s rank correlation and Mann–Kendall test, with the residuals plotted to determine the validity of using a linear trend.

It has already been noted that the different estimates of ENSO variability can affect the determination of a trend (e.g., Solomon and Newman, 2012). Furthermore, as trends computed over a short period can be uncertain and TPI values are estimated from 2011 onwards, the trend is calculated over the chosen period (1962–2011) and also over small variations in the period. Twenty-four additional estimates of the trend for each data set are calculated by varying the start-year between 1960 and 1964 and the end-year between 2009 and 2013. If the 24 estimates are outside the range of the 90% confidence interval for the chosen period, the interval will be increased to include these estimates.

To calculate the corrected ENSO indices for each SST data set considered, the tropical trend is first subtracted from the SSTs, after which the SSTs are averaged regionally for the various indices, and the anomalies calculated based on the 1976–2014 climatological base period (corrected index). For comparison, the SST anomalies are also calculated without removing the tropical trend (raw index). A range of possible values for the SST-based indices is computed for the raw indices by considering the three datasets and for the corrected indices by the range of the 1962–2011 trend.
2.4 | SST-based ENSO indices

Two SST-based ENSO indices are considered: Niño3.4 SST anomalies in the region 5°S–5°N, 120°–170°W and Niño. West SST anomalies in the region of 0°–15°N and 130°–150°E (Figure 1). As ENSO events are seasonal, sustained SST anomalies are required. There are a variety of methods for classifying ENSO events.

For Niño3.4, NOAA uses the Oceanic Niño Index, or the 3-month running mean Niño3.4 anomaly, where an El Niño (La Niña) event occurs when the index is greater (less) than 0.5 (−0.5) for five consecutive months (Trenberth, 1997; Kousky and Higgins, 2007). The base period for the NOAA index is shifted every 5 years to account for changes in the climatology. The Bureau of Meteorology (BoM) in Australia consider an El Niño (La Niña) event when values persist above 0.8 (below −0.8), although other factors such as low level winds and the SOI are also considered (BoM, 2017a). Here we classify ENSO events as five consecutive months or longer where at least 50% of the running 3-month mean corrected anomalies exceed 0.65 (or −0.65), halfway between the two commonly used thresholds of 0.5 and 0.8. Using two-digit accuracy is warranted as SST measurement uncertainties are better captured by combining several datasets and using a probabilistic approach.

The Niño.West index is less common and therefore has fewer definitions, however is included as it better represents SST anomalies in the West Pacific. The Japan Meteorological Agency define a warm (cool) event as six consecutive months of the 5-month running mean above 0.15 (below −0.15). Here, for consistency we chose to use the same five running 3-month averages as Niño3.4, with a higher threshold (0.25 and −0.25) to compensate for the shorter consecutive period requirement. While the Niño.West index is not used directly to determine El Niño or La Niña events, it indicates the strength of the warming/cooling in the west outside of the Niño3.4 region.

It is important to note that the choice of threshold or classification is somewhat arbitrary and dependent on the operational requirements of the monitoring centre. Discrete states are used to simplify the continuum of ENSO patterns and strengths.

2.5 | Other ENSO-related variables

ENSO is an ocean–atmosphere coupled system and so it is important to assess whether the subtraction of the tropical warming trend aligns with anomalies in the atmosphere and ocean. Therefore, the most recent ENSO cycle, 2014–2016, is considered in reference to the previous events using both oceanic and atmospheric indicators. Occurring at the end of the time series, these events will have the largest deviation from the raw index. For comparison with atmospheric variables low level zonal winds (NCEP-NCAR CDAS-1 reanalysis; Kalnay et al., 1996; Kistler et al., 2001) and outgoing longwave radiation, OLR (NCEP CPC global monthly OLR) are used. During an El Niño (La Niña) event, OLR increases (decreases) over the Maritime Continent and decreases (increases) over the central Pacific, although the OLR pattern varies between ENSO events (Chiodi and Harrison, 2015). Similarly, during an El Niño event, there is a decrease (increase) in the easterly trade winds over the central Pacific, and an increase (decrease) in the western Pacific.

As an estimate of the ocean response, the warm water volume (WWV) is used (Meinen and McPhaden, 2000). Three-month running mean of the standardized anomalies of the depth of the 20 °C potential temperature isotherm (using NCEP Global Ocean Data Assimilation System data; Bhanger and Xue, 2004) are averaged over the region 5°S–5°N, 120°E–80°W for the full Pacific, as well as 5°S–5°N, 160°–120°W for the east-central Pacific only from IRI Climate Data Library. The WWV anomalies have been found to be good predictors of ENSO SST (Meinen and McPhaden, 2000), although there has been a noted decrease in the WWV variability post 2000 (Hu et al., 2013).

3 | RESULTS AND DISCUSSION

3.1 | SST trends

Figure 1 highlights the spatial variation in trend across the Tropics and for the various indices: Niño.West index covers an area with enhanced warming (0.11–0.16 °C/decade, 90% confidence interval), greater than the near neutral trend for the Niño3.4 region (−0.06 to 0.14 °C/decade, 90% confidence interval).

The trend in the average tropical SST varies between data set and month in Figure 3, although all months have a significant monotonic increasing trend based on the Mann–Kendall test (p < .01). Based on the 90% confidence intervals, the ERSST data set has the greatest trend (varying between 0.07 and 0.15 °C/decade; blue diagonal in Figure 3). Although, there was considerable overlap between the datasets with the COBE data set tropical trend varying between 0.06 and 0.12 °C/decade (green dots in Figure 3), followed by HadISST, with a trend between 0.05 and 0.12 °C/decade (red in Figure 3). The month with the smallest trend was January (0.05–0.13 °C/decade across the three datasets) and the largest trend in June (0.08–0.15 °C/decade), although again there were overlaps between the various months. The 24 estimates for each data set with modified start- and end-years all fall within the 90% confidence interval of the 1962–2011 trend. Therefore, the 90% confidence intervals for the 1962–2011 trend were used for the remainder of the analysis.

Plotting the residuals shows no apparent problems with using linear regression for most months and datasets (see Figures S2–S4, Supporting Information). The exceptions are January where there appears to be a slight decrease in the variance for all three datasets, as well as ERSST in
December. However, as the other months do not show any obvious pattern, the linear trend is assumed to be sufficient for the rest of the analysis. To extend further into the future (or past), the tropical SSTs should be checked to determine if they still follow the same linear trend.

3.2 | Updated SSTs and ENSO event classification

Overall, the variations in Niño3.4 index are small between the three SST datasets, while the difference between the corrected and raw time series is larger at the start and end of the study period (Figure 4). For 1962–1971, the average difference between the three raw datasets is 0.13 °C while the average difference between the raw and the corrected datasets is 0.28 °C. For the later period, 2007–2016, the average difference between the raw datasets is 0.05 °C while the average difference between the raw and the corrected datasets is 0.16 °C. Due to the subtraction of the tropical warming trend, SST anomalies increase in the early portion of the time series and decrease in the latter half.
In the case of the Niño.West index, the smaller variability in the index (anomalies between $-1$ and $1 \, ^\circ\text{C}$) makes the difference between datasets more noticeable in Figure 4. However, when averaged over a 10-year period, the difference between the three raw datasets is $0.11 \, ^\circ\text{C}$ for 1962–1971 and $0.09 \, ^\circ\text{C}$ for 2007–2016. As with the Niño3.4 index, the average difference between the raw and corrected Niño.West index is $0.28$ and $0.16 \, ^\circ\text{C}$ for 1962–1971 and 2007–2016, respectively.

Table 1 lists the events based on the updated ENSO event classification for the raw and corrected time series, which include the major ENSO events since 1976. For comparison, the dates from three major operational centres: BoM (BoM, 2017a), NOAA, (NOAA, 2017), and JMA (JMA, 2017) are also included. As one would expect from the relationship between the IPO and ENSO, seen in the SST trend over the climatology period (Figure S1), El Niño events dominated the mid-part of the record when the IPO was positive (from 1976

| Year          | El Niño New | NOAA | BoM | JMA | Year          | La Niña New | NOAA | BoM | JMA |
|---------------|-------------|------|-----|-----|---------------|-------------|------|-----|-----|
| 1976–1977     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1976–1977     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1977–1978     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1978–1979     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1979–1980     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1980–1981     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1982–1983     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1983–1984     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1986–1987     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1987–1988     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1991–1992     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1992–1993     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1993–1994     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1994–1995     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 1997–1998     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 1998–1999     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 2002–2003     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 2003–2004     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 2004–2005     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 2005–2006     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 2007–2008     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 2009–2010     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 2010–2011     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 2011–2012     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |
| 2015–2016     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     | 2016–2017     | ✓ ✓         | ✓ ✓  | ✓ ✓ |     |

**Figure 5** Time series for La Niña and El Niño events for the raw series (left) and corrected series (right), using the ERSST data set and mean 1962–2011 trend only. The grey dotted lines indicate the $0.5/0.8$ and $-0.5/-0.8$ thresholds.
to 1997; six El Niño events against three La Niña), while in the IPO negative period (1998–2016) La Niña events dominates (five events against three El Niño). The events under the updated criteria also match with other operational centres (NOAA, BoM, and JMA). In every case where all three operational centres agree, both the raw and corrected updated event classifications also mark an El Niño or La Niña, indicating that the detrending has a negligible impact on the classification when the event is strong. There are notable differences, however, for borderline cases such as the La Niña in 2016 or the El Niños in 1976–1977 and 2004–2005. For these three cases, their classification depends on if the correction for background warming was made. While there may still be differences in classification between centres for these borderline events based on operational requirements, not accounting for the background warming can also have an effect.

The time evolution of the ENSO events starting from the month of January prior to the peak of the event is plotted using raw and corrected series (Figure 5). Overall the impact of removing the tropical warming trend on any individual event is small, although some subtle differences are noteworthy. The 2016 event would not make the −0.65 threshold requirement in the raw series and is only recorded once corrected. After detrending, the 2010 La Niña event becomes the third largest La Niña in magnitude, much closer to the 1988 and 1973 events. For El Niño events, 2015, 1997, and 1982 are the strongest El Niño events in the record of similar magnitude, compared with the raw datasets where 2015 is noticeably stronger. These three events are also not significantly different when considering other SST indices besides Niño3.4 (Huang et al., 2016). A similar result was found when using the COBE and HadISST datasets (not shown).

Overall, the background warming trend will lead to a difference of ±0.2 °C throughout a 30-year period (provided that an appropriate climatology period is used). While the choice of threshold is somewhat subjective, correcting or not can change whether an ENSO event is declared for borderline events. As there is not such a sharp distinction between ENSO event and non-ENSO event, it is important to investigate SST anomalies along with other atmospheric and oceanic variables for these events.

### 3.3 The recent ENSO cycle: 2014–2016

The past 3 years captures the full ENSO cycle: a neutral period in 2014, strong El Niño of 2015, and possible 2016 La Niña, with the Niño3.4 values in Table 2. Based on the classification of ENSO events (five consecutive 3-month running means greater or less than 0.65/−0.65 for Niño3.4), there was an El Niño event from April 2015 to April 2016 in the raw data set, slightly longer than for the corrected index (May 2015 to April 2016). The difference for the second half of 2016 is greater, with no 3-month running means below the La Niña threshold for the raw time series, while a La Niña event would have been declared for August 2016 to December 2016 once corrected. Both the La Niña and El Niño events cover the months August–December; therefore, these months are chosen for the composite analyses.

Table 2 demonstrates how the coupled atmosphere–ocean system responds when considering anomalies of OLR, zonal wind at 850 hPa (U850), WWV, and corrected SST averaged over 5°S–5°N over the recent 3 years. In 2014, minor positive and negative anomalies are visible with no consistent signal in the first three variables and small positive values for the WWV. While the raw index suggested that an El Niño event developed in late 2014 (not shown),

| Niño3.4 raw | Niño3.4 corrected |
|-------------|-------------------|
| Min | Max | # | Min | Max | % |
| Neutral 2014 3 | −0.18 | 0.05 | −0.44 | −0.17 | 0 |
| 2014 4 | 0.17 | 0.25 | 0 | −0.10 | 0.13 | 0 |
| 2014 5 | 0.32 | 0.43 | 0 | 0.09 | 0.30 | 0 |
| 2014 6 | 0.24 | 0.37 | 0 | 0.02 | 0.23 | 0 |
| 2014 7 | 0.14 | 0.26 | 0 | −0.11 | 0.12 | 0 |
| 2014 8 | 0.14 | 0.22 | 0 | −0.12 | 0.09 | 0 |
| 2014 9 | 0.28 | 0.34 | 0 | 0.02 | 0.21 | 0 |
| 2014 10 | 0.54 | 0.58 | 0 | 0.29 | 0.46 | 0 |
| 2014 11 | 0.66 | 0.71 | 3 | 0.44 | 0.59 | 0 |
| 2014 12 | 0.68 | 0.76 | 3 | 0.46 | 0.66 | 0 |
| 2015 1 | 0.56 | 0.65 | 0 | 0.30 | 0.54 | 0 |
| 2015 2 | 0.50 | 0.57 | 0 | 0.24 | 0.45 | 0 |
| 2015 3 | 0.63 | 0.67 | 1 | 0.34 | 0.55 | 0 |
| 2015 4 | 0.81 | 0.83 | 3 | 0.55 | 0.70 | 25 |

El Niño 2015 5 | 1.07 | 1.10 | 3 | 0.80 | 0.96 | 100 |
| 2015 6 | 1.29 | 1.33 | 3 | 1.05 | 1.16 | 100 |
| 2015 7 | 1.58 | 1.64 | 3 | 1.35 | 1.46 | 100 |
| 2015 8 | 1.83 | 1.94 | 3 | 1.61 | 1.76 | 100 |
| 2015 9 | 2.05 | 2.22 | 3 | 1.83 | 2.07 | 100 |
| 2015 10 | 2.28 | 2.49 | 3 | 2.06 | 2.36 | 100 |
| 2015 11 | 2.45 | 2.69 | 3 | 2.23 | 2.57 | 100 |
| 2015 12 | 2.59 | 2.75 | 3 | 2.36 | 2.63 | 100 |
| 2016 1 | 2.42 | 2.53 | 3 | 2.19 | 2.41 | 100 |
| 2016 2 | 2.12 | 2.20 | 3 | 1.88 | 2.03 | 100 |
| 2016 3 | 1.62 | 1.69 | 3 | 1.37 | 1.54 | 100 |
| 2016 4 | 1.05 | 1.08 | 3 | 0.78 | 0.93 | 100 |
| 2016 5 | 0.47 | 0.55 | 0 | 0.21 | 0.40 | 0 |
| 2016 6 | −0.07 | 0.10 | 0 | −0.32 | −0.05 | 0 |
| 2016 7 | −0.37 | −0.22 | 0 | −0.61 | −0.37 | 0 |

La Niña 2016 8 | −0.52 | −0.39 | 0 | −0.76 | −0.54 | 0 |
| 2016 9 | −0.61 | −0.55 | 0 | −0.87 | −0.70 | 100 |
| 2016 10 | −0.64 | −0.62 | 0 | −0.92 | −0.75 | 100 |
| 2016 11 | −0.65 | −0.60 | 0 | −0.89 | −0.73 | 100 |
| 2016 12 | −0.50 | −0.48 | 0 | −0.79 | −0.60 | 75 |

Table 2: 2014–2016 Niño3.4 values for the raw and corrected series (3-month running mean). El Niño and La Niña events are classified as in section 2.4. The number of datasets before correction (#) and percentage of corrected estimates (%) passing the threshold are also given.
the corrected index along with atmospheric indicators confirm that indeed no El Niño developed at that time. From January 2015, the WWV in the eastern and central Pacific starts to increase. In May 2015, a classic El Niño signal appears in the other three variables: warm SST in the central and eastern Pacific, negative OLR anomalies just east of the international dateline and positive anomalies to the west, and stronger westerlies over western and central Pacific. These conditions are maintained until April 2016. The WWV for the entire Pacific and for the east-central Pacific become negative around December 2015 and February 2016, respectively. Both remain negative for the remainder of 2016. Between April and July 2016, the other anomalies reverse to a La Niña pattern beginning in July/August 2016 with opposite anomalies compared to the previous El Niño, albeit much weaker. Therefore, OLR, trade winds, and subsurface temperatures indicate corresponding patterns of neutral, El Niño, and a La Niña year between 2014 and 2016, as was found based on the corrected threshold in Table 2.

Composites of OLR for previous ENSO events are comparable with the events 2014–2016 (Figure 7). Non-zero values for the El Niño and La Niña events (Figure 7d,e) are shown only when they are significantly different from the neutral years based on the Mann–Whitney $U$ test ($p < .05$). The 2016 La Niña (August–December) event displays the critical shift in the repartitioning of OLR across the Tropics: increased cloudiness over the Maritime Continent (negative OLR values), with the clearer skies along the central Pacific (Figure 7a,d). Extratropical anomalies present in the single 2016 event map are not present in the composites map. This result indicates that these extratropical anomalies, while sizeable during a single event, are not connected to ENSO variability and hence are averaged out when several events are combined. The 2015 El Niño (August–December) event has a similar pattern to previous El Niño events, with larger anomalies over the Maritime Continent and central equatorial Pacific (Figure 7b,e). The composite of neutral events (Figure 7f) shows weak anomalies restricted about the equator, which may be due to the tendency in SST towards a more La Niña like pattern (there is no significant trend in the tropical OLR between 1976 and 2016). Overall though, the individual 2014 event (Figure 7c) displays a much less consistent pattern than the 2015 or 2016 events, as would be expected during a neutral year.

The corrected SST anomalies are also similarly coherency between the 2014–2016 events and their respective composites (Figure 8), although extratropical teleconnections can be found in the La Niña and El Niño SST composites for the Pacific (Figure 8d,e). As with the OLR composites, non-zero values for the El Niño and La Niña events (Figure 8d,e) are shown only when they are significantly different from the neutral years based on the Mann–Whitney $U$ test ($p < .05$). The 2016 map, once corrected, looks similar to the composite from previous La Niña events, albeit without the cooling along the South America coastline (Figure 8a). The 2015 event also follows an El Niño pattern, but with greater warming along the eastern equatorial Pacific, highlighting the strength of the event (Figure 8b). The average SST for the Tropics (30°S–30°N) in 2015 is also warmer than normal, possibly due to the large El Niño. In 2014, the SSTs in the tropical Pacific are on average, near normal (Figure 8c). This is similar to the neutral event composite, apart from slight cooling in the equatorial eastern Pacific. The neutral years should be near zero, as the tropical warming trend has been removed.

The OLR and SST anomalies in the Indian Ocean in 2016 and 2015 are both not present in the La Niña and El Niño composites in Figures 7 and 8, highlighting that there is also
variability in the spatial patterns of ENSO events. The Niño.
West index for 2014–2016 is in Table 3 for both raw and cor-
rected indices. Once corrected, the cold and warm events from
the western Pacific SST index, align closer to the Niño3.4
index with a Niño.West event in 2016. The occurrence of
both a warm Niño.West event and La Niña event in 2016, as
well as a cold Niño.West event and El Niño event in 2015,
indicates a stronger western Pacific component and possible
Indian Ocean influence. L’Heureux et al. (2017) also found a
stronger west and central Pacific signature for the 2015 El
Niño. Seasonal differences between the eastern and western
Indian Ocean can be classified using the Indian Ocean Dipole
(IOD) index (Saji et al., 1999). Negative IOD events occur
when the Indian Ocean is warmer than normal in the east and

![FIGURE 7](image)

**FIGURE 7** Mean August–December OLR anomalies for particular years (top) and composites of previous events (bottom; 8 La Niña events, 9 El Niño
events, and 21 neutral events). For the La Niña and El Niño composites, only grid boxes that are significantly different from neutral events are shown (based
on the Mann–Whitney U test). Composites are taken for all events 1976–2013

![FIGURE 8](image)

**FIGURE 8** Mean August–December SST anomalies for particular years (top) and composites of previous events (bottom; 8 La Niña events, 9 El Niño
events, and 21 neutral events). For the La Niña and El Niño composites, only grid boxes that are significantly different from neutral events are shown (based
on the Mann–Whitney U test). Composites are taken for all events 1976–2013
TABLE 3 2014–2016 NiñoWest values for the raw and corrected series (3-month running mean). Events are classified as in section 2.4. The number of datasets before correction (#) and percentage of corrected estimates (%) passing the threshold are also given.

|                | NiñoWest raw | NiñoWest detrended |
|----------------|--------------|---------------------|
|                | Min Max #    | Min Max %           |
| Neutral        |              |                     |
| 2014           | 0.20 0.42 1  | −0.03 0.29 10       |
| 2014           | 0.17 0.40 2  | −0.05 0.26 3        |
| 2014           | 0.24 0.50 2  | 0.02 0.34 60        |
| 2014           | 0.28 0.50 3  | 0.07 0.31 50        |
| 2014           | 0.32 0.43 3  | 0.11 0.27 5         |
| 2014           | 0.24 0.32 2  | 0.03 0.14 0         |
| 2014           | 0.21 0.33 1  | 0.01 0.15 0         |
| 2014           | 0.19 0.32 1  | −0.02 0.15 0        |
| 2014           | 0.19 0.37 2  | −0.02 0.21 0        |
| 2014           | 0.22 0.42 2  | 0.01 0.27 10        |
| 2015           | 0.18 0.38 2  | −0.05 0.22 0        |
| 2015           | 0.06 0.16 0  | −0.17 −0.01 0       |
| 2015           | −0.03 −0.01 0| −0.31 −0.14 25      |
| 2015           | −0.06 −0.02 0| −0.35 −0.17 50      |
| 2015           | −0.02 0.05 0 | −0.29 −0.11 15      |
| Cold           |              |                     |
| 2015           | −0.09 −0.04 0| −0.33 −0.21 80      |
| 2015           | −0.20 −0.07 0| −0.43 −0.27 100     |
| 2015           | −0.21 −0.06 0| −0.43 −0.26 100     |
| 2015           | −0.18 0.02 0 | −0.40 −0.17 70      |
| 2015           | −0.10 0.06 0 | −0.32 −0.12 50      |
| 2015           | −0.14 0.06 0 | −0.37 −0.10 55      |
| 2015           | −0.14 0.09 0 | −0.37 −0.07 40      |
| 2016           | −0.17 0.09 0 | −0.41 −0.08 60      |
| 2016           | −0.12 0.11 0 | −0.36 −0.06 50      |
| 2016           | −0.03 0.16 0 | −0.28 −0.03 10      |
| 2016           | 0.14 0.21 2  | −0.10 0.01 0        |
| 2016           | 0.31 0.38 3  | 0.01 0.22 0         |
| Warm           |              |                     |
| 2016           | 0.43 0.60 3  | 0.13 0.43 60        |
| 2016           | 0.55 0.69 3  | 0.29 0.52 100       |
| 2016           | 0.59 0.72 3  | 0.36 0.56 100       |
| 2016           | 0.61 0.69 3  | 0.38 0.52 100       |
| 2016           | 0.60 0.65 3  | 0.37 0.47 100       |
| 2016           | 0.51 0.57 3  | 0.28 0.40 100       |
| 2016           | 0.49 0.57 3  | 0.25 0.41 100       |
| 2017           | 0.50 0.54 3  | 0.24 0.38 100       |
| 2017           | 0.50 0.55 3  | 0.24 0.39 100       |

Cooler in the west, often bringing more rainfall to the Maritime Continent. The 2015 El Niño and 2016 La Niña correspond to positive and negative IOD events, respectively (BoM, 2017b). This West Pacific signature of the 2016 and 2015 events, the type found to be more prominent in recent years (e.g., Ren and Jin, 2011; Capotondi et al., 2015; Wang and Ren, 2017) is difficult to capture using a single grid box index. Therefore, while a single grid box index with the tropical trending removed can be a useful tool in classifying ENSO events, it will not provide a complete picture of the various ENSO flavours.

4 | CONCLUSION

Single grid-box SST anomalies in the Pacific can be a useful diagnostic tool for ENSO; however, background warming can affect the results. Warming of the tropical SSTs has the potential to offset cold ENSO events and enhance warm ones. Here we revisited the Niño3.4 index, from which we subtracted the background tropical warming trend and used a new ENSO classification to assess how warming has affected the ENSO indices.

Overall, there is a clear warming trend in the tropical SST temperatures between 1962 and 2011. This trend has an effect on the borderline ENSO cases, such as in 2016, where removing the tropical trend can make a difference in the classification of events. The warming trend has less effect on the major events where all operational centres agree, although the removal of the trend can alter the magnitudes of those events. Comparing the last 3 years and the composite of previous events for both ocean and atmospheric indicators shows that the Niño3.4 index with the tropical warming trend removed still identifies the classic ENSO signatures. However, even with the correction applied, a single grid-box SST index may not capture the various ENSO flavours.

While the focus here is on observed SST-based indices, predicted index values will also likely be affected, due to the input of observed SSTs and other observations into the models. With tropical SST temperatures continuing to rise, accounting for the warming will become more important in the monitoring and prediction of ENSO events.

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