Impact of Different ENSO Regimes on Southwest Pacific Tropical Cyclones

SAVIN S. CHAND, JOHN L. McBRIDE, KEVIN J. TORY, AND MATTHEW C. WHEELER

Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Victoria, Australia

KEVIN J. E. WALSH

School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia

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ABSTRACT

The influence of different types of ENSO on tropical cyclone (TC) interannual variability in the central southwest Pacific region (5°-25°S, 170°E-170°W) is investigated. Using empirical orthogonal function analysis and an agglomerative hierarchical clustering of early tropical cyclone season Pacific sea surface temperature, years are classified into four separate regimes (i.e., canonical El Niño, canonical La Niña, positive-neutral, and negative-neutral) for the period between 1970 and 2009. These regimes are found to have a large impact on TC genesis over the central southwest Pacific region. Both the canonical El Niño and the positive-neutral years have increased numbers of cyclones, with an average of 4.3 yr⁻¹ for positive-neutral and 4.7 yr⁻¹ for canonical El Niño. In contrast, during a La Niña and negative-neutral events, substantially fewer TCs (averages of 2.2 and 2.4 yr⁻¹, respectively) are observed in the central southwest Pacific. The enhancement of TC numbers in both canonical El Niño and positive-neutral years is associated with the extension of favorable low-level cyclonic relative vorticity, and low vertical wind shear eastward across the date line. Relative humidity and SST are also very conducive for genesis in this region during canonical El Niño and positive-neutral events. The patterns are quite different, however, with the favorable conditions concentrated in the date line region for the positive-neutral, as compared with conditions farther eastward for the canonical El Niño regime. A significant result of the study is the demonstration that ENSO-neutral events can be objectively clustered into two separate regimes, each with very different impacts on TC genesis.

1. Introduction

The dominant climate process affecting the tropical Pacific on interannual time scales is the El Niño-Southern Oscillation (ENSO) phenomenon. Traditionally, ENSO is characterized by anomalously warm and cool sea surface temperatures (SSTs) in the cold tongue region of the eastern Pacific during El Niño and La Niña events, respectively (e.g., Wyrski 1975; Rasmusson and Carpenter 1982). A number of recent studies (e.g., Trenberth and Stepaniak 2001; Larkin and Harrison 2005; Ashok et al. 2007; Kug et al. 2009; Kao and Yu 2009) have also identified a nontraditional type of El Niño [referred to here as the “El Niño Modoki,” as in Ashok et al. (2007)] with the above-normal SSTs confined more to the central Pacific region flanked by below-normal SSTs on the eastern and western sides. In this paper, we examine how different patterns of Pacific interannual SST variability modulate tropical cyclone (TC) activity in the central southwest Pacific region, which is defined here as the area between 5° and 25°S, and 170°E and 170°W.

A pioneering study of the influence of traditional El Niño (the “canonical El Niño”) and La Niña events on tropical cyclone activity was made by Nicholls (1979), who explored the potential for seasonal prediction of Australian region TCs. Subsequent studies led to the confirmation of the relationship not only for the Australian basin but also for the other TC basins of the world [see, e.g., McBride (1995) and the review by Camargo et al. (2010)]. In the southwest Pacific, TC activity was found to systematically shift northeastward during canonical El Niño events, reaching as far as the Cook Islands and French Polynesia with the greatest incidence around the date line, and the Fiji islands
(e.g., Revell and Goulter 1986a,b; Basheer and Zheng 1995; Chand and Walsh 2009; Vincent et al. 2011). Simultaneously, low activity dominates the Coral Sea and Australian regions (e.g., Nicholls 1984; Evans and Allan 1992; Basheer and Zheng 1995; Ramsay et al. 2008). In contrast, the reverse was found to occur during La Niña events when TC activity is displaced southward into the Coral Sea and Australian region with relatively low activity east of the date line.

Over recent years, investigations relating to the impact of El Niño Modoki on TCs have also garnered attention. Kim et al. (2009), for example, found that unlike canonical El Niño, El Niño Modoki events are associated with greater-than-average TC frequency in the North Atlantic basin with increasing landfall potential along the Gulf of Mexico coast and Central America. Similarly, El Niño Modoki is found to substantially modulate TC frequency (Chen and Tam 2010), genesis distribution (Kim et al. 2011), and tracks (Hong et al. 2011) in the western North Pacific basin. Above-normal TCs are also observed in the South China Sea during the June–August months of the El Niño Modoki years (Chen 2011).

Building on these investigations, the present paper examines the association between tropical cyclone activity and different ENSO regimes for the central southwest Pacific region. Here ENSO regimes are identified using statistical methods such as an empirical orthogonal function (EOF) analysis (e.g., McBride et al. 2003; Ashok et al. 2007) and a hierarchical clustering technique (e.g., Kao and Yu 2009; Singh et al. 2011). As evident later in the paper, we are able to identify four separate ENSO regimes, each having a distinct impact on the central southwest Pacific TCs. The first two of these regimes are associated with the well-documented traditional El Niño and La Niña events. Interestingly, the other two regimes are a split of the traditional ENSO-neutral phase; one of these regimes resembles the El Niño Modoki pattern with anomalous cooling in the eastern and western Pacific and the other has a La Niña–like signature but with anomalous warming extending farther east to the date line. Identifying these two regimes here for the first time and demonstrating their different impacts on the southwest Pacific TCs are the main highlights of this work.

The remainder of the paper is structured as follows. Section 2 describes datasets and analysis methods used in this study. Results are given in sections 3. Finally, a summary is given in section 4.

2. Data and methods

The TC data used here are obtained from the National Climate Centre, Australian Bureau of Meteorology (e.g., Kuleshov et al. 2008, 2010). Only data for the Southern Hemisphere TC season (i.e., November–April) for the period beginning November 1970 and ending April 2009 are considered. Consistent with Chand and Walsh (2009), we have included all TCs that formed in the central southwest Pacific region (5°–25°S, 170°E–170°W).

Monthly values of the Niño-3.4 indices are obtained from the website of the National Oceanic and Atmospheric Administration (NOAA, http://www.esrl.noaa.gov/psd/data/climateindices/list/). The SST data are from Met Office Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al. 2003). Atmospheric variables are extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis I products (Kalnay et al. 1996).

To determine different ENSO regimes and their impact on the southwest Pacific TCs, an agglomerative hierarchical clustering (AHC) technique is applied on the early Southern Hemisphere TC season [i.e., November–January (NDJ)] SST anomalies over the tropical Pacific (i.e., 30°S–30°N, 120°E–60°W) for the period between the 1970 and 2009 seasons. The AHC technique, as described in Kao and Yu (2009), is a nonlinear composite procedure that continuously merges similar SST maps into clusters. Its implementation is composed of three steps. The first step identifies the similarity or dissimilarity by computing Euclidean distance, defined as the root-mean-squared distance, between all SST maps. The second step involves grouping SST maps that are in close proximity to each other into a binary, hierarchical tree (dendrogram) using a linkage function. The linkage function uses the distance information generated in the first step to determine the proximity of objects to each other. Here we used a linkage function based on the Ward method (Ward 1963), as it is considered appropriate for Euclidean distances. The final step determines where to cut the hierarchical tree into clusters, such that all SST maps below each cut are assigned to a single cluster. Moreover, we have also applied an EOF analysis to supplement the results of our AHC technique. EOF analysis is performed here using the singular value decomposition (SVD) method (e.g., Emery and Thomson 2001; von Storch and Zwiers 1999). The amplitudes of the two leading eigenfunctions are used to aid visualization of different ENSO regimes.

Similar ENSO regimes (not shown) were obtained using the austral summer season (i.e., December–February) SST anomalies; however, for the purpose of this study, early TC season SST anomalies are preferred because of their relatively stronger ENSO signatures on the southwest Pacific TCs (e.g., Chand et al. 2010) and
on Australian TCs (e.g., Nicholls 1984; Kuleshov et al. 2009).

3. Results

a. The ENSO regimes

The first and the second modes of the EOF analysis performed on the NDJ SST anomalies for the period 1970/71–2008/09 are shown in Fig. 1. These modes explain 62% and 11%, respectively, of the variance in the data. The first mode (Fig. 1a) shows the well-documented classical ENSO spatial structure that centers in the equatorial eastern Pacific and extends into the central Pacific. In the associated time series (Fig. 1b) years corresponding to the values ≥0.5σ (σ being the standard deviation) of the normalized expansion coefficients correspond to the canonical El Niño years, whereas years of values ≤−0.5σ are the canonical La Niña years. These years are in broad agreement with the classical El Niño and La Niña events defined by Trenberth (1997) using the Niño-3.4 index (not shown). Similarly, Fig. 1c shows the structure of the El Niño Modoki with anomalously warm SSTs in the central equatorial Pacific region between about 170°E and 160°W and extending toward the subtropics during its positive phase, flanked by cooler equatorial anomalies on either side (e.g., Kao and Yu 2009).

Figure 2a plots each year in [first principal component (PC1), second PC (PC2)] phase space, PC1 and PC2 being the amplitudes of the normalized expansion coefficients of the first EOF (EOF1) and the second EOF (EOF2), respectively. For comparison, a dendrogram resulting from the AHC is shown in Fig. 2b. Clusterings of years are clearly evident using both the EOF and AHC methods. Using the EOF method, it is found that canonical El Niño years cluster in the region where PC1 is ≥0.5σ and PC2 is ≤0.5σ, while the canonical La Niña years cluster in the region where PC1 is ≤−0.5σ and PC2 is ≤0.5σ. Similar clustering results are obtained using the AHC technique at the cutting level 1 in Fig. 2b except for the year 1977, which it classifies as a canonical El Niño. Note that at the cutting level 2, AHC is also able to isolate events associated with extreme canonical ENSO phenomena. For example, years such as 1972, 1982, and 1997 were the strongest canonical El Niños on record and are clustered separately from relatively weaker El Niño events (see red and orange trees of the dendrogram in Fig. 2b). Similarly, La Niña events of two different strengths are identified as separate clusters by the clustering method (dark and light blue trees). For the purpose of this study, canonical El Niño and La Niña regimes are considered from the cutting level 1. Therefore, our canonical El Niño regime, as obtained using the November–January SST anomalies for the period between 1970 and 2008, includes the events of 1972, 1976, 1977, 1982, 1986, 1987, 1991, 1994, 1997, 2002, and 2006. Similarly, events corresponding to our canonical La Niña regime are 1970, 1971, 1973, 1974, 1975, 1984, 1988, 1998, 1999, 2000, 2005, 2007, and 2008. Note that since our SST anomalies used in the computation are spread over two calendar years (i.e., November and December of the first year, and January of the second year), the first of the years is used to refer to a particular ENSO event.

Moreover, there are also years when values of PC1 lie within approximately ±0.5σ and PC2 > 0. These years...
are also grouped as a single cluster by the AHC method at the cutting level 1. According to the Trenberth (1997) classification, all these years would be considered as the ENSO-neutral condition. However, the AHC is further able to separate these years into the two distinct clusters at the cutting level 2 (see black and green trees of the dendrogram in Fig. 2b). Years associated with each of these two clusters also lie on the opposite sides of $\text{PC1} = 0$, indicating that they are possible variants of our canonical El Niño and La Niña regimes. That is, events of 1978, 1979, 1980, 1992, 1993, 2003, and 2004, identified as a separate cluster by AHC, lie on the “El Niño” side of the PC1 values. This cluster is referred to as the “positive-neutral” regime. Likewise, the events of 1981, 1983, 1985, 1989, 1995, 1996, and 2001, identified as a separate cluster by AHC, lie on the “La Niña” side of the PC1 values, and this cluster is referred to as the “negative-neutral” regime. Indeed, the composite of SST anomalies for positive-neutral and negative-neutral regimes show two distinct patterns. The positive-neutral regime, to some extent, resembles the canonical El Niño pattern but with anomalous cooling in the eastern Pacific near the west coast of South America (cf. Figs. 3c,a). The negative-neutral regime rather has a La Niña-like signature but with anomalous warming extending farther east to the date line and with a slightly narrower band of anomalous equatorial cooling east of the date line (cf. Figs. 3d,b). Arguably, SST patterns of both these regimes may be interpreted as a part of El Niño Modoki, which can occur in different forms with varying degrees of amplitude (Yu and Kim 2010). However, instead of subjectively selecting events of the strongest EOF2 as El Niño Modoki events, we considered the objective classification of clusters as optimal and treated positive-neutral and negative-neutral as separate events.

It is important to emphasize here that some questions have been raised in the past on the existence of different types of ENSO events. For example, Ashok et al. (2007) indicated that canonical ENSO and El Niño Modoki were two independent phenomena, but Takahashi et al. (2011) argued that they do not describe different phenomena but rather a nonlinear evolution of ENSO. Regardless, there is a general consensus that different types of ENSO do occur, and in subsequent sections we explore how the four ENSO regimes identified here modulate TC genesis in the central southwest Pacific.

b. TC frequency and ENSO regimes

The annual TC frequencies over the central southwest Pacific region are binned into their corresponding ENSO regimes. The bootstrap resampling method is applied to construct the 95% confidence intervals of the mean TC frequency for each regime (Fig. 4b). Following the procedure described in Chu and Wang (1997) and Chen (2011), the two-sample permutation method, together with their modified $U$ statistic test, is applied at the 5% significance level to compare mean TC frequency in different ENSO regimes (Table 1)—the
reader is referred to Chu and Wang (1997) for details of the method.

Results show that TCs formed in the central southwest Pacific show large variations between the regimes (Fig. 4 and Table 1). On average, the highest number of TCs (~4.3 yr⁻¹) can be observed during a positive-neutral event, while about 4.0 TCs are observed in a canonical El Niño event. These values are significantly greater than the average number of TCs (~2.4) observed in a negative-neutral event. In a La Niña event, fewer TCs (~2.2) are observed, and this is not significantly different from the mean number of TCs noted in a negative-neutral regime. However, it is significantly smaller than the number of TCs formed during a positive-neutral or a canonical El Niño event.

c. TC genesis distribution and the associated environmental conditions

Probability density functions (PDFs) are used to describe the spatial distribution of TC genesis in each ENSO regime—the word genesis being defined here objectively as the first track point of each TC. The PDFs are computed from the anisotropic Gaussian functions (e.g., Ramsay et al. 2008; Chand and Walsh 2009) using a 2.5° × 2.5° smoothing window. The input to the PDF calculations is the dataset of TC genesis positions across the entire South Pacific and is not restricted to the study region. Moreover, to understand the physical mechanisms accounting for the observed variations in TC genesis distribution in different ENSO regimes, we examine composites of anomalous 850-hPa winds, the associated 850-hPa relative vorticity anomalies, the vertical wind shear of the zonal winds between the 850- and 200-hPa levels, and the midtropospheric (i.e., between 500- and 700-hPa levels) relative humidity anomalies. In previous studies changes in these fields are found to be the main factors contributing to TC genesis variability in the central southwest Pacific (e.g., Chand and Walsh 2009, 2011).

Consistent with the analysis of Chand and Walsh (2009), TCs forming during a canonical El Niño event are distributed throughout the central southwest Pacific with a maximum density centered around 170°-175°E and spreading eastward (Fig. 5a). A secondary maximum is also evident farther east around 165°W. This pattern of genesis distribution can be explained by the large-scale circulation features. An eastward extension of 850-hPa westerly wind anomalies associated with the Walker circulation equatorward of 10°S, together with the concomitant easterly anomalies poleward of about 15°S, gives rise to a zone of anomalous cyclonic relative vorticity favoring TC development in the central southwest Pacific (Fig. 6a). Extension of low values of vertical wind shear of zonal winds as far to the east as 165°W is also likely a contributing factor for the observed genesis distribution. These regions also have anomalously large thermodynamic environments, such as SST (Fig. 3a) and relative humidity (Fig. 7a), that considerably favor TC development during canonical El Niño events.

During La Niña events, TC genesis positions are displaced westward and poleward relative to a canonical El
Niño event. Here TCs mainly form in the Coral Sea region with a maximum density centered around 15°S, 160°–165°E and a secondary maximum observed northeast of Fiji (Fig. 5b). This pattern of genesis distribution coincides with the associated favorable environmental conditions (Figs. 3b, 6b, 7b). Unlike a canonical El Niño event, large-scale environmental conditions, particularly relative vorticity and wind shear, substantially suppress TC activity east of about 170°E during a La Niña event.

In a positive-neutral event, genesis in the central southwest Pacific region is usually confined in the area between 170°E and 175°W (Fig. 5c), where large-scale environmental conditions such as anomalously large cyclonic relative vorticity and low vertical wind shear are quite favorable for formation (Fig. 6c). Corresponding thermodynamic variables such as anomalous SSTs (Fig. 3c) and relative humidity (Fig. 7c) are also quite favorable for TC development during positive-neutral events. The associated southeastward-moving tracks (not shown) often pose a substantial threat to the

<table>
<thead>
<tr>
<th>Variable 1</th>
<th>Variable 2</th>
<th>$U$ statistic (95% confidence intervals)</th>
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<tbody>
<tr>
<td>El Niño Modoki</td>
<td>Canonical El Niño</td>
<td>0.54 (−1.99, 1.95)</td>
</tr>
<tr>
<td>El Niño Modoki</td>
<td>Canonical La Niña</td>
<td>2.52 (−1.89, 1.88)</td>
</tr>
<tr>
<td>El Niño Modoki</td>
<td>Neutral</td>
<td>1.86 (−2.00, 1.83)</td>
</tr>
<tr>
<td>Canonical El Niño</td>
<td>Canonical La Niña</td>
<td>3.29 (−1.99, 1.99)</td>
</tr>
<tr>
<td>Canonical El Niño</td>
<td>Neutral</td>
<td>2.13 (−1.86, 1.86)</td>
</tr>
<tr>
<td>Canonical La Niña</td>
<td>Neutral</td>
<td>0.30 (−1.86, 1.86)</td>
</tr>
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Fiji islands. TCs can also form as far to the east as 160°W but at a lower rate compared to a canonical El Niño event. For completeness, we have also examined the TC genesis distribution for the negative-neutral regime (Fig. 5d). Here, unlike the canonical ENSO and positive-neutral regimes, genesis density is weakly distributed east of the date line, where environmental conditions are less favorable for genesis (Figs. 3d, 6d, 7d). However, genesis here is more common in the Coral Sea region but at a lower rate than La Niña.

4. Summary

Using an EOF analysis of SSTs and a supplementary clustering technique, we have classified Southern Hemisphere TC seasons into four separate regimes (i.e., canonical El Niño, canonical La Niña, positive-neutral, and negative-neutral) for the period between 1970/71 and 2008/09. Results indicate marked modulations of the central southwest Pacific (5°–25°S, 170°E–170°W) TC genesis between different regimes.

The maximum frequency of TCs (~4.3 yr$^{-1}$) occurs during a positive-neutral event. Here the majority of TCs form between 170°E and 175°W, where large-scale environmental conditions such as low-level cyclonic relative vorticity, vertical wind shear of zonal winds, SSTs and relative humidity are more favorable for TC development than elsewhere in the entire southwest Pacific. A slightly lower number of TCs (~4.0 yr$^{-1}$) is observed during a canonical El Niño event with a maximum density centered around 170°–175°E and spreading eastward, consistent with an eastward extension of the favorable environmental conditions. During a La Niña event, fewer TCs (~2.2 yr$^{-1}$) are observed in the central southwest Pacific and genesis maxima shift westward compared to the canonical El Niño event. About 2.4 TCs form in the central southwest Pacific region during a negative-neutral event. During La Niña
and negative-neutral events, large-scale environmental conditions are less favorable for TC development in the study domain, particularly east of the date line.

In summary, we have shown here the impact of different ENSO regimes on TCs in the central southwest Pacific. In particular, we have demonstrated here for the first time that traditional ENSO-neutral events can be objectively clustered into two separate regimes, each having a distinct and significant impact on TC frequency and genesis distribution in the central southwest Pacific. The extent to which these regimes can modulate tropical cyclones in other basins, particularly in the Australian region, could form the topic of another investigation.

![Fig. 5. Anisotropic Gaussian density distribution (shadings: in number of genesis per year and per 2.5° × 2.5° boxes) and actual genesis positions (crosses) of TCs for different ENSO regimes over the South Pacific basin; the central southwest Pacific basin between 170°E and 170°W is indicated.](image)

![Fig. 6. Composites anomalies of November–April 850-hPa wind vectors (m s⁻¹), zero contour of vertical wind shear of zonal winds between 850- and 200-hPa levels, and 850-hPa relative vorticity anomalies (shadings: ×10⁻⁶ s⁻¹) for the four regimes. Blue indicates anomalously more cyclonic relative vorticity.](image)
Fig. 7. As in Fig. 6, but for the midtropospheric relative humidity anomalies (%). Shadings denote positive anomalies.

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